

Suisun Marsh Tidal Marsh and Aquatic Habitats Conceptual Model

Chapter 3: Tidal Marsh

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Suisun Marsh Habitat Management, Restoration and Preservation Plan

Primary Authors:

**Stuart Siegel, WWR
Christina Toms, WWR
Dan Gillenwater, WWR**

Contributing Authors:

Chris Enright, DWR

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3 Tidal Marsh

The purpose of this conceptual model is to describe the processes influencing tidal marshlands of Suisun Marsh and their ecosystem functions, how these and other processes control the evolution of marsh restoration sites, and key considerations in planning large-scale tidal restoration in Suisun Marsh. Suisun Marsh historically was a tidal marsh system comprising brackish marshes with higher salinities towards the west and in the fall and lower salinities in the east and in winter and spring. Today, somewhat less than 8,000 acres of tidal marsh remain, comprising a mixture of relict historic marsh (e.g., Rush Ranch), “centennial marsh” formed along bay margins from accretion of Sierra Nevada hydraulic mining sediment (e.g., Lower Joice Island), marsh along sloughs with reduced tidal exchange due to diking (e.g., along many slough banks), and restored marsh (e.g., Ryer Island) (**Figure 3-1**).

Tidal marshlands provide a range of ecosystem functions for many birds, fish, mammals and plants including several special status species. Tidal marshlands provide breeding habitats, forage opportunities, refuge, and many pathways of food web productivity. Expanding these ecosystem functions through large-scale restoration is a key focus of the Suisun Marsh Plan. This Chapter 3 of the Tidal Marsh-Aquatic Habitats Conceptual Model describes lays the foundation for restoration approaches. This Chapter draws extensively upon Chapter 1, Physical Processes, and leads into Chapter 4, Species. The boundary between a tidal marsh and the aquatic environment is a fuzzy line; the large tidal sloughs within the tidal marshlands are aquatic just as are the large tidal sloughs surrounded by levees, albeit with many differences in processes and functions.

This Chapter covers the following subjects:

- A description of tidal marshlands of Suisun including elevational (inundation) characteristics, planform variations, and channel networks (Section 3.1)
- Processes of marsh evolution (Section 3.2)
- Overview of ecological functions at stages along the evolutionary trajectory of restored tidal marshes (Section 3.3)
- Key considerations in large-scale restoration planning (Section 3.4)
- Assumptions, uncertainties, and research needs (Section 3.5)

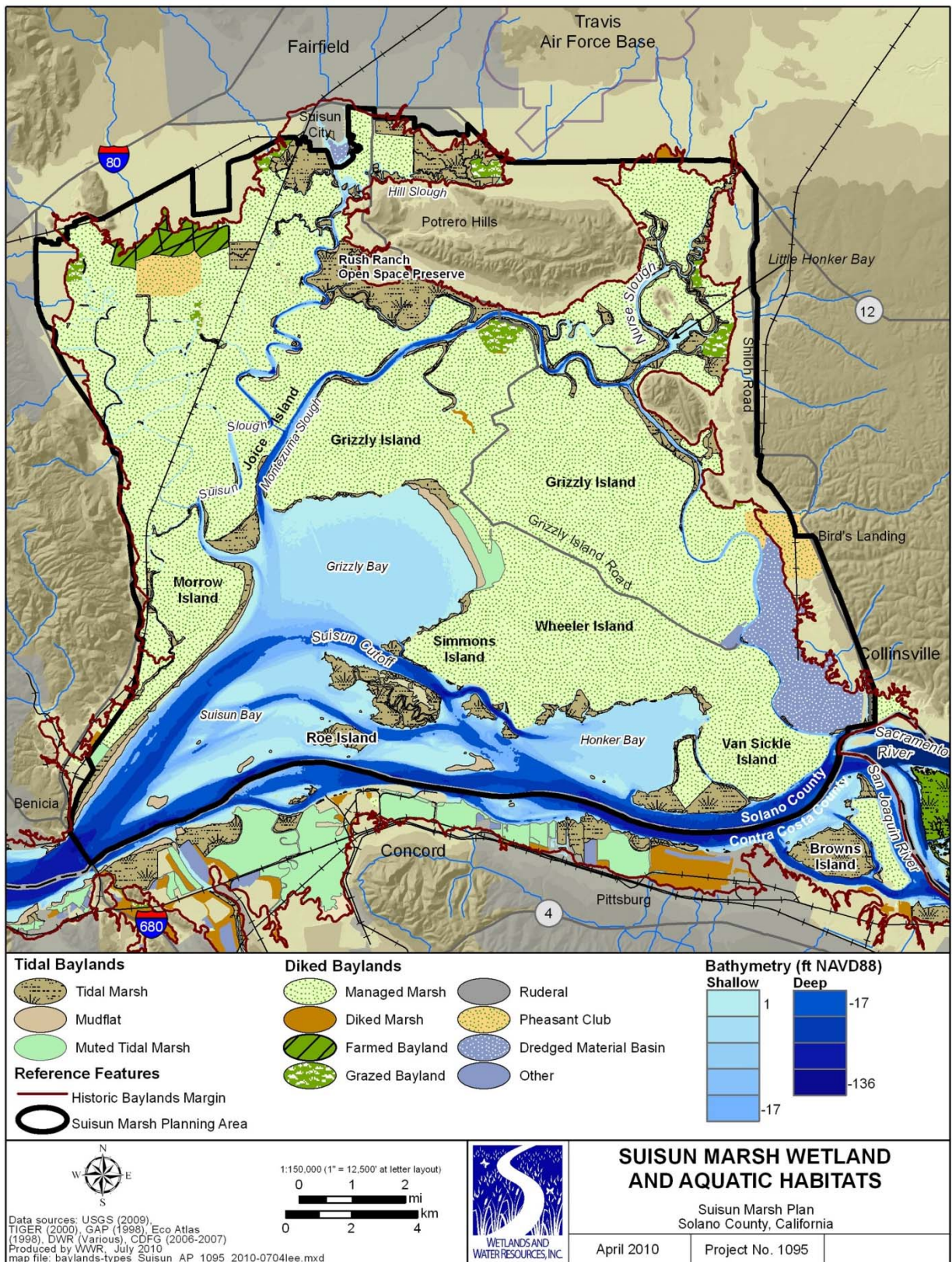


Figure 3-1. Suisun Marsh Wetland Types

3.1 Tidal Marsh Habitats of Suisun

Due to its position within the Estuary of the steepest salinity gradient from the freshwater Delta to the saline San Pablo Bay, the tidal marshes of Suisun are the most diverse marshes in terms of their flora and their providing ecological functions for a great number of fish and wildlife species, supporting species adapted to both fresh and saline conditions. Tidal marshes consist of several distinct features described in this section: vegetated marsh plains, tidal channels, ponds and pannes within the marsh plain, and aquatic and upland edges. Here we describe the tidal marshes of Suisun, considering elevation differences (Section 3.1.1), planform characteristics (Section 3.1.2), and tidal channels (Section 3.1.3). Diked managed marsh is described very briefly (Section 0) mainly in the context of lands being suitable for tidal restoration; a separate Managed Wetlands Conceptual Model describes managed wetlands in detail.

3.1.1 Vertical Variation in Marsh Habitats

At the most fundamental level, the frequency, magnitude, and duration of tidal inundation exerts the single greatest control on tidal marsh functions and processes. Inundation regimes are controlled through the interaction between relative marsh elevation and tidal action. Constrictions on tidal exchange, such as undersized channels, hydraulic roughness of marsh vegetation, and depressions on the marsh plain mediate the role of marsh elevation (Atwater and Hedel 1976; Hinde 1954; Peinado et al. 1992). This vertical mosaic provides complex habitats for many fish and wildlife species (**Figure 3-2**).

Even for plants, which live most of their life cycle fixed in place, habitat diversity can be important with respect to pollinators or in controlling environmental factors such as erosion or drainage. Plant distribution relative to topography is influenced by inundation regime predominantly and salinity secondarily (Adams 1990; Goals Project 2000). In the saline tidal marshes of the lower Estuary, emergent vegetation does not grow very low in the tidal range due to salt stress (Mahall and Park 1976). In the freshwater marshes of the upper Estuary in the Delta, emergent vegetation can grow below low tide due to lack of salt stress. The brackish tidal marshes of Suisun exhibit an intermediate condition (**Figure 3-3**); how low plants can grow relative to the tides reflects the salt stress environment which itself varies strongly and results in a very diverse marsh flora and a range of elevations down to which emergent vegetation is found.

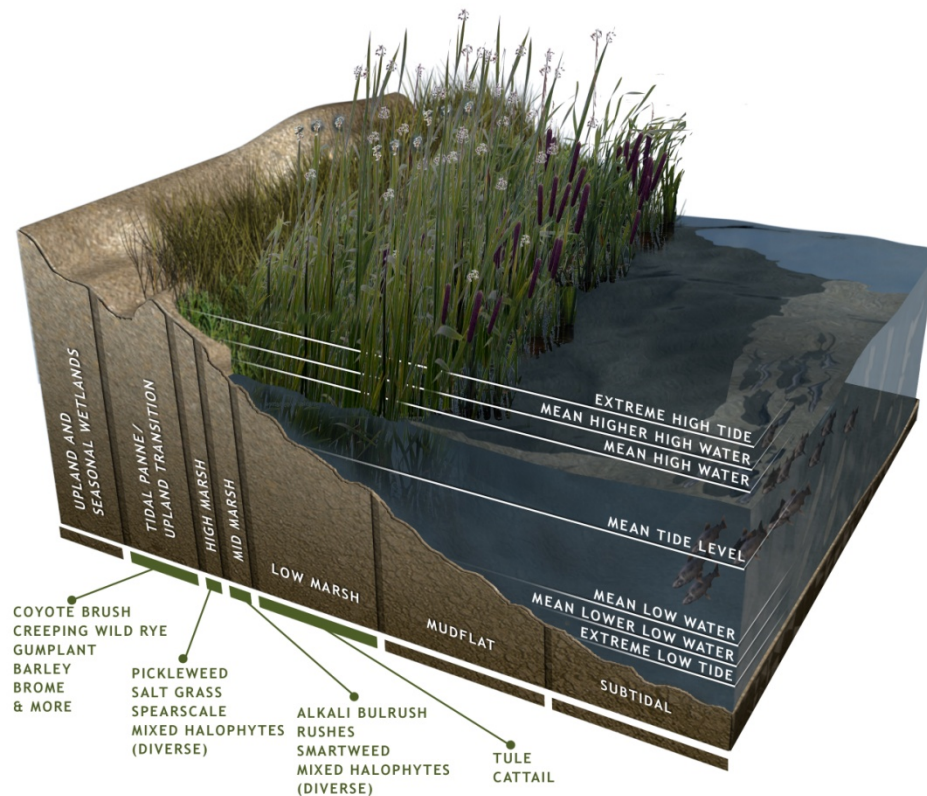


Figure 3-2. Vertical Zonation Cross Section in Suisun Tidal Marshes

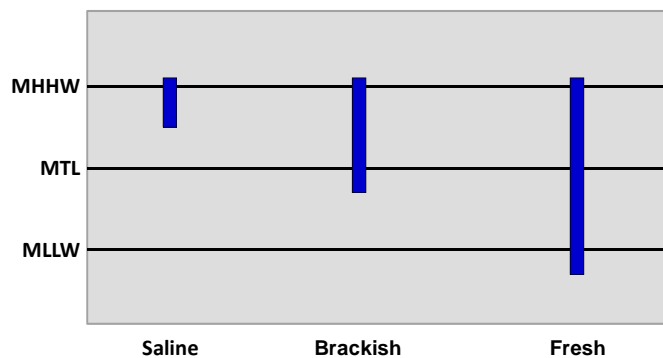


Figure 3-3. Tidal Marsh Vegetation Vertical Growth Range by Salinity Regime

3.1.2 Planform Variation in Tidal Marsh

Suisun Marsh, like much of the San Francisco Estuary, has seen most of its tidal wetlands diked and converted to other land uses (mainly waterfowl clubs in Suisun), with few remnant tidal marshes remaining. Today's Suisun Marsh has two landform types of tidal marsh: complex or interior marshes and fringing marshes.

Holocene marshes are larger patches, have a high area-to-edge ratio, and typically have high geomorphic complexity. Natural and restored complex marshes are found at Rush Ranch Open Space Preserve, Hill Slough, Peytonia Slough, Boynton Slough, Roe Island, Ryer Island, and two small islands in Suisun Bay (**Figure 3-1**). Holocene marshes typically have large marsh plains, a network of sinuous tidal channels, ponds and pannes on the marsh plain and, when located adjacent to uplands, an upland transition. Rush Ranch (**Figure 3-4**) illustrates this marsh type.

Centennial marshes (e.g., the lower tip of Joice Island) can be large in size and with a range of edge:area ratios depending on location. These marshes formed mainly in the later 19th century and early 20th century by emergent vegetation colonizing newly deposited sediment supplied from Sierra Nevada hydraulic gold mining. Their fairly rapid formation has resulted in relatively low geomorphic complexity including much less sinuous tidal channels.

Fringing marsh, in contrast, exists along the outboard side of dikes and generally has formed since diking began and the original sloughs began to shrink in response to the reduced tidal prism. Fringing marsh is found along many of the sloughs in Suisun Marsh and along the bayfront levees around Suisun Bay (**Figure 3-1**). These marshes vary in size and vegetation composition, are generally far less complex geomorphically, and have a low area-to-edge ratio. In some locations, substantial sediment has deposited along the exterior of the levee allowing vegetation to colonize and expand outward for large distances into the slough. In other areas, fringing marsh is limited to a narrow band along the exterior levee bank. In most cases, channel structure is limited to small, relatively straight segments with comparatively little access provided to the marsh plain. Fringing marshes lack connection with the upland transition, are often found in small, discontinuous segments, and can limit movement of terrestrial marsh species. Nurse Slough (**Figure 3-4**) illustrates a larger patch of fringing marsh.



Figure 3-4. Examples of Interior and Fringing Marsh

3.1.3 Tidal Channels

Tidal channels within tidal marshes perform two fundamental functions. First, tidal channels are the conduits through which water, sediment, nutrients, and aquatic organisms circulate into, around, and out of the marsh, providing a critical connectivity mechanism between marsh plain and open water environments. This distributary function directly controls most of the physical conditions in a tidal marsh to which plants and wildlife are subject. In turn, this distributary function reflects the marsh geomorphology, tidal range, sediment loads, marsh substrate, and marsh vegetation. Consequently, channel morphology is a primary forcing function for ecology (Callaway 2001; French and Reed 2001; Mitsch and Gosselink 2000; Weinstein and Kreeger 2000). Second, channels provide essential habitat for a wide variety of fish and wildlife species. Channel edges provide habitat for species such as the endangered California clapper rail (*Rallus longirostris obsoletus*), a bird that nests and feeds along cordgrass vegetated channel banks (Albertson and Evens 2000). Channels provide shallow water habitat for dabbling and diving ducks (Takekawa et al. 2000). Channels provide forage habitat and ingress/egress routes for a wide variety of fish species, and previous researchers have attributed population size reductions to the tremendous loss of tidal marsh channel habitat in the San Francisco Estuary in the late 19th century (Bennett and Moyle 1996).

3.1.4 Managed Marsh

About 52,000 acres in Suisun are diked marsh managed largely as waterfowl hunting clubs. These managed areas are separated from the tidal sloughs by and water exchange is controlled by gated culverts and other water control structures. Waterfowl club managers control the timing and duration of flooding to promote growth of waterfowl food plants. The marsh surface is often graded to provide uniform flooding and draining, thus eliminating plant zonation. Ditches are dug to increase water circulation throughout the pond. Typical plant species include *Bolboschoenus maritimus*, *Sarcocornia pacifica*, *Cotula coronopifolia* (brass buttons), *Atriplex triangularis*, and *Echinocloa crusgall*, (watergrass). These lands were tidal marsh historically and tidal marsh restoration in Suisun generally will occur on portions of these lands. The separate *Managed Wetlands Conceptual Model* describes these wetlands.

3.2 Physical Evolution of Restored Marshes

[This section requires further revision]

The primary mechanism for tidal marsh restoration in Suisun will be the breaching of levees to reconnect diked areas to tidal action. Once the levee breaches are established, natural physical and biological processes will guide site evolution and the provision of a range of ecological functions. As covered in detail in Chapter 4, Species, the particular ecological functions provided by a restoration site depend upon its stage of evolution. This view of a restored tidal marsh thus recognizes the continually changing roles that restored marshes will provide as each site changes from its initial restoration condition toward a “dynamic equilibrium” or “mature” marsh, a state that itself is dynamic with changing conditions of sea level, salinity, sediment supply, and plant growth.

This section describes what controls the physical evolution of restored tidal marshes:

- General restoration site evolution conceptual model (Section 3.2.1)
- Baseline site elevations (Section 3.2.2)
- Inundation regimes (Section 3.2.3)
- Relative marsh surface elevation (Section 3.2.4)
- Vegetation colonization (Section 3.2.5)
- Geomorphic evolution (Section 3.2.6)

3.2.1 General Restoration Site Evolution Conceptual Model

The evolution of a restored tidal marsh is in general based upon the interaction of initial site conditions, marsh morphology (internal site conditions), hydrodynamics (external site conditions), and anticipated drivers of future change (**Figure 3-5**). Natural tidal marshes have historically been characterized as ‘evolving’ towards a state of maturity, and are often thought of as ‘old’ or ‘new’ tidal marsh based on their morphology, location within a watershed, and geologic provenance. However, recent studies in marsh morphodynamics have emphasized the fact that tidal marshes respond rapidly to environmental drivers

such as relative sea level rise, sediment supply, the estuarine salinity gradient, and inundation regime, and that their morphology, vegetation community, and ecological functions are often a short-term balance amongst these drivers, or a “dynamic equilibrium” (French and Reed 2001). Consequently, the evolution of a restored tidal marsh from an initial state of a subsided managed wetland is essentially a shift in the short-term balance between the primary drivers of marsh morphology.

The general process for evolution of a restored marsh has been described in previous papers (Adams 1990, Friedrichs and Perry 2001, Siegel 2002, Williams and Orr 2002; Williams 2001). Most of these papers describe restoration of diked, drained baylands within the lower San Francisco Estuary subsided to subtidal elevations with little to no vegetative substrate, such as salt ponds or agricultural fields. Most of the diked, managed wetlands in Suisun Marsh on which restoration to tidal wetlands can occur, in contrast, are actively managed to support a significant coverage of emergent marsh vegetation (**Figure 3-1**). When diked, managed wetlands are restored to full tidal action two primary physical processes change: (1) the depth, duration, and frequency of inundation of the marsh plain, and (2) the concentrations of water quality constituents such as suspended sediment and salinity transported between marsh habitats and their source waters. What makes Suisun distinct from many lower Estuary restorations is the emergent vegetation, which can influence site evolution processes and it can “jumpstart” providing ecological functions. Changes in these processes can induce changes in marsh vegetation community composition and structure, thus inducing changes in the habitat functions provided by these communities.

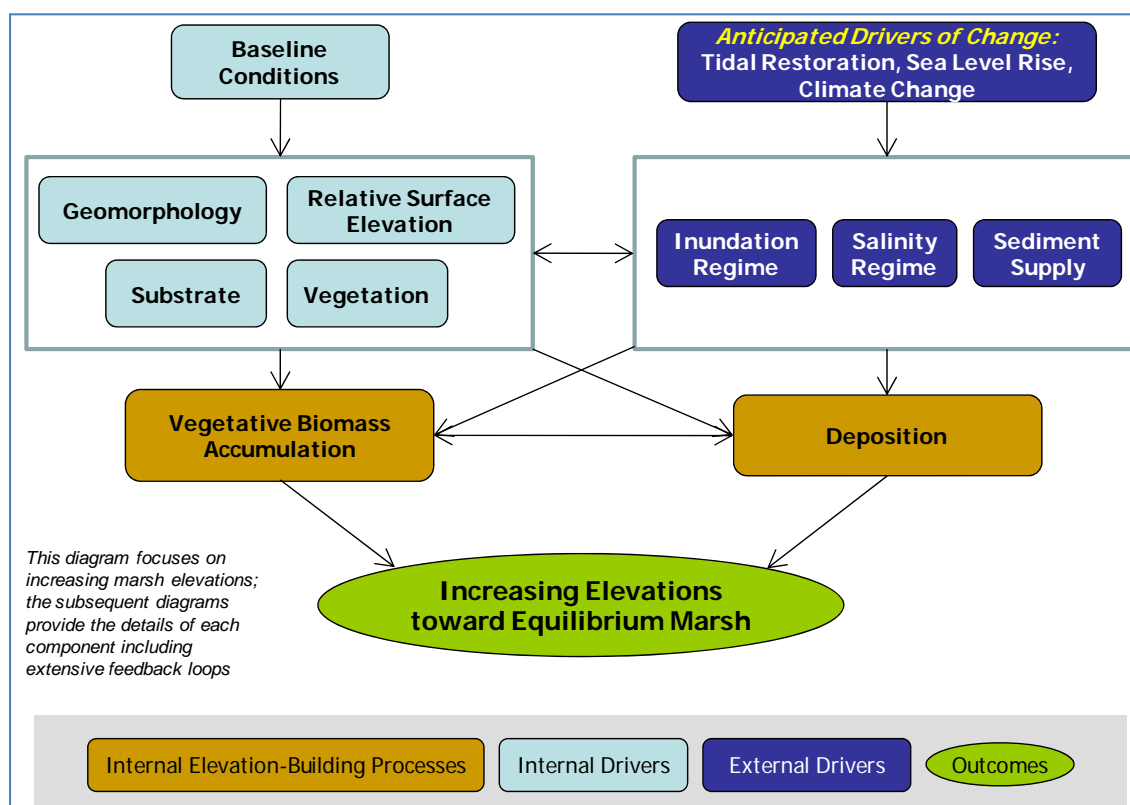


Figure 3-5. General Tidal Marsh Restoration Site Evolution Conceptual Model

This general tidal marsh restoration site evolution conceptual model considers the increasing marsh elevation, a proxy for inundation regime, as the primary outcome. Driving this site evolution are the sediment deposition and emergent vegetation biomass accumulation, both of which raise site elevations. Driving these two “intermediate” drivers are a suite of internal marsh conditions and external site drivers, themselves a function of baseline site conditions and the major drivers of future change (see Chapter 1).

The ultimate outcomes sought by tidal marsh restoration in Suisun, such as support of native estuarine species, will shift over time in nature, quantity, location, and quality as each restoration site matures. At the Suisun-wide scale, a mosaic of restoring tidal marshes evolving at different rates will result in a broad range of tidal marsh functions and ecological support. Consequently, understanding the processes that drive restoration site evolution will inform understanding how each site and Suisun Marsh as a whole will provide a variety of ecological functions over time.

3.2.2 Baseline Site Elevations and Initial Conditions

Baseline site elevation is the dominant factor defining the “initial condition”, with substrate characteristics and emergent vegetation being the next most important drivers. In Suisun Marsh, the baseline condition is subsided diked lands (**Figure 3-6** and **Figure 3-7**) with a median elevation of MLLW and extending in the most subsided areas to about six feet below MLLW (see **Figure 1-7** in Chapter 1).

The varying elevations of the diked marshes of Suisun translates into different “starting points” for restoration projects, thus providing the potential for a mosaic of initial conditions following restoration. The evolution of restored landscapes is then controlled by the rates at which sites increase in elevation, which is controlled by sediment supply and plant matter accumulation (see Section 3.2.4 below). Sea level rise will act to “delay” marsh evolution though the magnitude of the effect will vary depending on the relative rates of sea level rise, sedimentation, and peat formation.

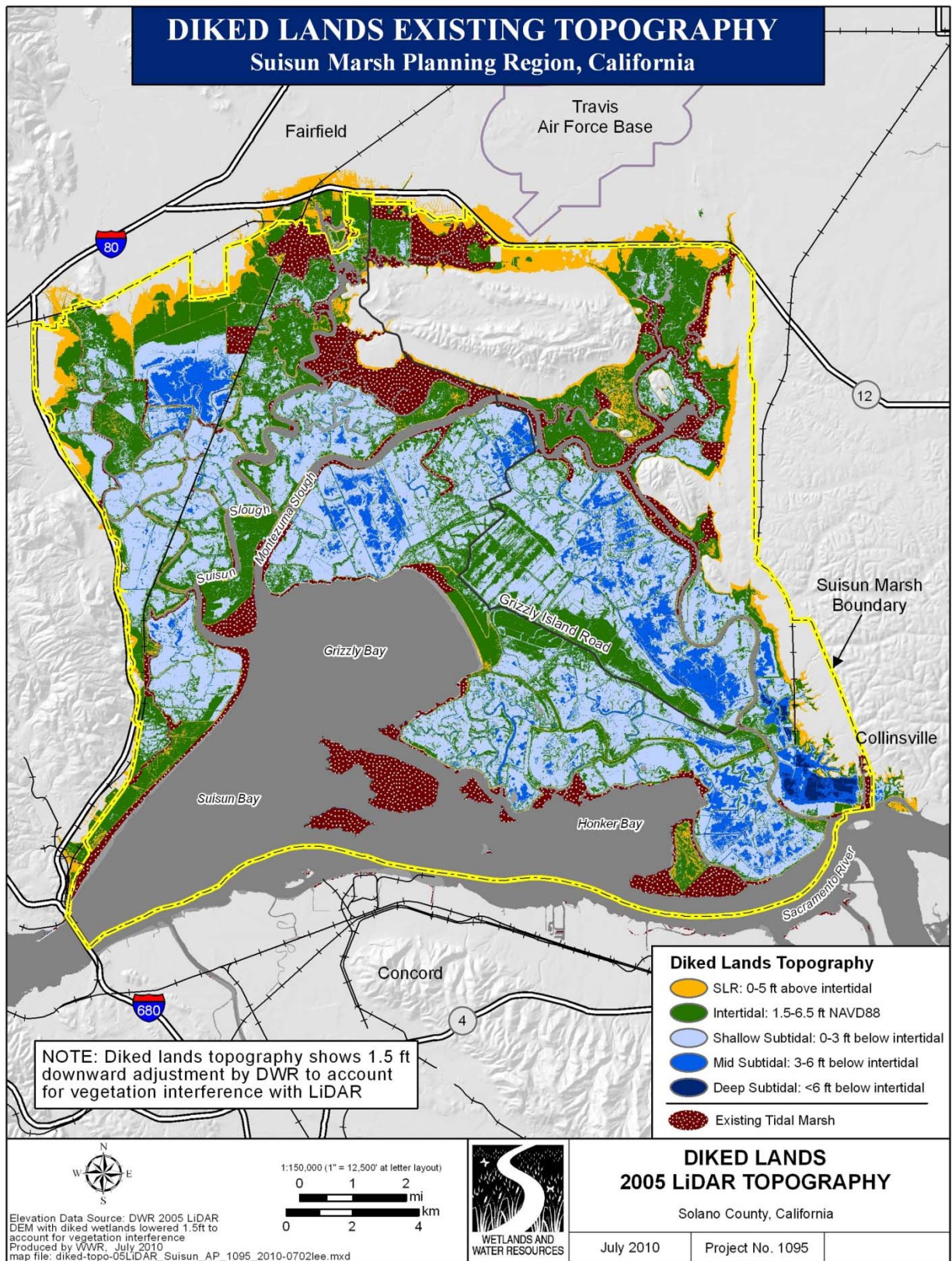


Figure 3-6. Diked Lands Topography

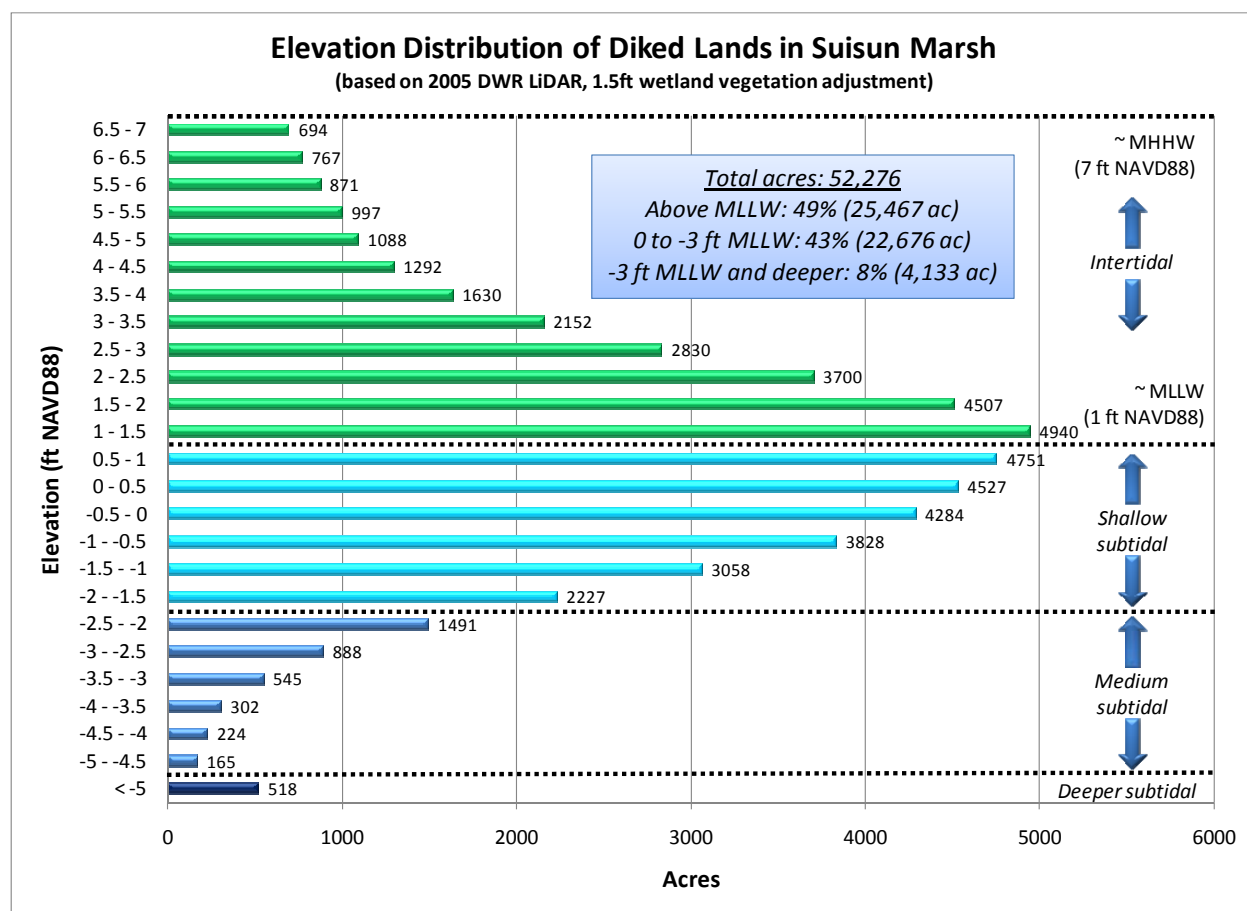


Figure 3-7. Histogram of Diked Lands Topography

3.2.3 Tidal Flooding and Inundation Regime

The inundation regime is defined as the frequency, duration, and depth of flooding by surface waters within a tidal marsh. Inundation regime is one of the most significant drivers of marsh ecology (Mitsch and Gosselink 2000) as it influences substrate character, vegetation composition, and hydrologic connectivity. Tidal marshes are distinguished from many other wetland systems in that their inundation regimes are driven by tidal cycles as well as seasonal precipitation cycles. Tides bring water into a wetland once or twice daily depending on whether tides are diurnal or semi diurnal. River flows, both local tributaries (e.g., local Suisun streams) and main-stem rivers (e.g., Delta outflow) can add additional depth and duration to the tidal inundation regime, though the frequency of such contributions is much lower and less predictable. Due to Suisun Marsh's position between the Sacramento-San Joaquin Delta and SF Bay, the tidal range within the marsh is smaller and elevated ("perched") relative to the tidal range in SF Bay (see Chapter 1).

The depth, duration, and frequency of inundation at a specific site are primarily determined by (1) the height of the tides, along with any watershed inputs, relative to the marsh surface elevation and (2) the nature of the hydraulic connection between the site and tidal source waters (Figure 3-8). High elevation marshes will

experience more shallow inundation depths and shorter duration of inundation relative to lower elevation marshes.

Distance from the tidal source, distance from channels, and drainage capability. Sites connected directly to large sloughs experience minimal tidal dampening whereas sites located at the headward end of small sloughs will experience some amount of tidal dampening. Hydraulic connectivity is also reduced in some restoration sites where undersized slough or breach geometry has not yet completely adjusted to the site's tidal prism. Such sites often experience poor drainage and extended inundation until tidal action widens and/or deepens the breach/slough system enough to accommodate the site's tidal prism. Depressions on the marsh surface such as pannes can pond water, leading to extended periods of generally shallow inundation and small surface rivulets. In addition, subsurface piping can act to drain the marsh plain with each tidal cycle, so soil infiltration can influence marsh drainage.

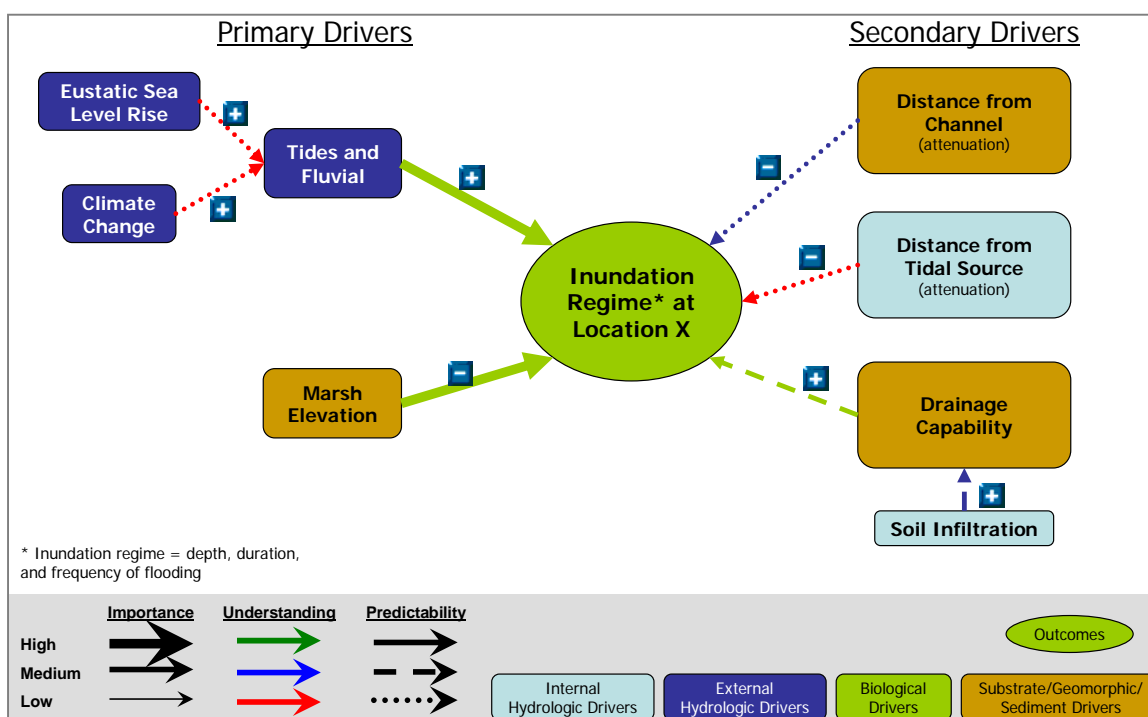


Figure 3-8. Conceptual Model of Inundation Regime

3.2.4 Relative Surface Elevation Dynamics

Relative surface elevation in a tidal marsh is the ground surface elevation relative to the range of the tides and is one of two primary drivers of the marsh inundation regime (Figure 3-9). The drivers acting to increase the relative elevation are (1) sediment deposition (SM D), which directly increases marsh elevations by adding new material to the marsh plain surface, (2) peat accumulation (SM PA), which describes the accumulation of organic material on the marsh plain, and (3) below-ground biomass production (SM BGBP), which describes the production of root and rhizome structures by plants. The

drivers acting to decrease the relative elevation are eustatic sea level rise, decomposition, subsidence, compaction, erosion, and desiccation.

Sediment deposition and peat accumulation are both influenced by the inundation regime (hydroperiod) (SM IR), which in turn is controlled by the relative marsh surface elevation. As the marsh plain elevation rises through sediment accretion and organic matter accumulation, the period of inundation decreases, and the rate of deposition declines. This interaction between hydroperiod and sediment supply provides a feedback mechanism which allows marshes to adjust their elevation to reach an 'equilibrium' point somewhere at an elevation below the highest spring tides (Williams and Orr 2002; Friedrichs and Perry 2001). For example, if sea level rises faster than the rate of vertical accretion, the relative elevation of the marsh decreases, which increases the hydroperiod. The increased hydroperiod facilitates an increase in sediment accretion by increasing the time suspended sediments have to settle on the marsh plain, which helps the marsh surface to keep pace with sea level rise. Conversely, if sea level rise is lower than the rate of vertical accretion, the marsh elevation will rise, resulting in a decreased hydroperiod and decreased sediment accretion.

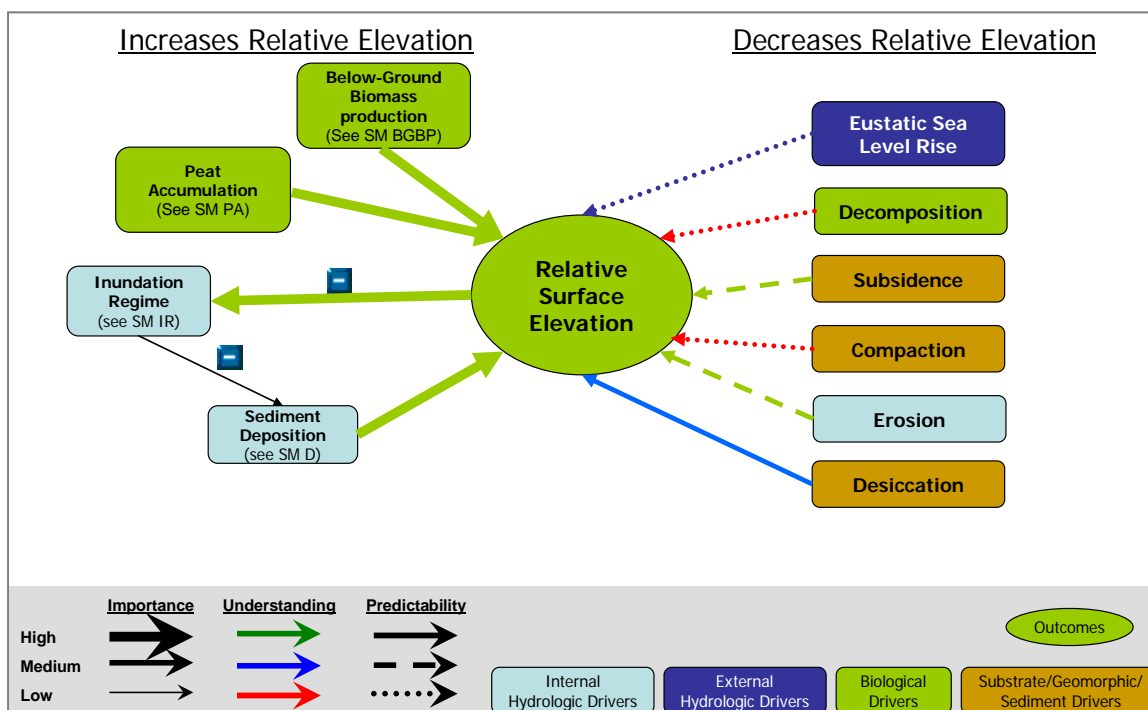


Figure 3-9. Relative Surface Elevation Conceptual Model

There are many factors that act to decrease relative marsh surface elevations. If rates of eustatic sea level rise are faster than rates of marsh accretion, SLR will reduce the relative surface elevation by raising the elevation of the tides. Decomposition breaks down organic material, thus reducing its volume. Subsidence, compaction, and desiccation are all processes which decrease the elevation of the marsh plain without

actually removing any material. Finally, erosion due to flushing by tidal and fluvial inputs will remove material from the surface of the marsh, thus reducing its elevation.

Deposition

The deposition of sediment on the marsh plain is one of the main processes by which marsh elevations are increased. The primary drivers influencing the amount and rate of deposition that occurs on the marsh plain are the inundation duration, the suspended sediment concentration, sediment grain size, marsh flow velocity, and salinity (**Figure 3-10**).

The inundation regime (see SM IR) describes the frequency, duration, and depth of surface waters within and/or covering a tidal marsh. Deposition can only occur when water is on the marsh plain; thus, inundation correlates positively with deposition, or the more time water covers the marsh plain the more deposition can occur. The key drivers influencing the inundation regime are the relative surface elevation (see SM RSE) and eustatic sea level rise (global changes in sea level). Tides are affected by sea level rise which in the San Francisco Estuary to date has acted to raise all the tidal datums relatively uniformly upward; the recent NOS update of tidal datums for the San Francisco Estuary added approximately 0.2 ft to all tides since the values from 25 years prior (see NOS web site, www.tidesandcurrents.noaa.gov).

Deposition is positively correlated with suspended sediment concentration because the more sediment that is available in the water column, the more that could potentially settle out. Suspended sediment data for Suisun Marsh can be found in Chapter 1. The suspended sediment concentration is positively influenced by (1) the position of the site in the estuary, or how close the site is to sources of sediments (rivers, creeks, bays, mudflats), (2) wind-generated waves which re-suspend sediments off the bottom, and (3) tide and storm flows, which bring sediment loads to the site from the various sources. Tide and storm flows are influenced primarily by (1) eustatic sea level rise, which increases the amount of water exchanged during the tidal cycle and (2) climate change, which acts to alter tide stage by changing storm flows, the frequency of El Nino events, and barometric pressure conditions, all of which contribute to changing surface water elevations.

Sediment grain size has a positive correlation with deposition because settling velocity generally increases with grain size. Bottom sediments in Suisun Bay typically range from silts and clays in shallow waters to silts and sands in deeper areas (Conomos and Peterson 1997). As with suspended sediment concentration, grain size is positively influenced by proximity to sediment sources and tide and storm flows. The increase in water velocities due to tidal action and storm flows allows greater suspension of larger particles than during slack-water conditions (Friedrichs and Perry 2001).

Marsh flow velocity has a negative correlation with deposition because increased water velocities will keep particles in suspension, precluding sedimentation. Marsh flow velocity is influenced by tide and storm flows, the presence of aquatic vegetation, and bed friction. The rapid movement of water into a marsh due to tides and storm flows will have a positive correlation with marsh flow velocity and act to decrease sedimentation.

The presence of aquatic vegetation can slow flow velocity significantly allowing sedimentation throughout the inundation period. Net deposition at vegetated sites at similar elevations can be up to five times greater than at adjacent unvegetated sites (Friedrichs and Perry 2001). Increasing bed friction will also cause a decrease in marsh flow velocity, which in turn will increase sediment deposition. Bed friction is positively influenced primarily by the bed grain size and substrate bulk density. Flow velocities also tend to decrease with distance from the water source (bay, river, stream channel), generally leading to increased deposition moving further up a channel network.

Finally, increases in salinity can increase sedimentation by promoting flocculation. This process increases sediment grain size, leading to higher rates of deposition. Salinity is discussed in-depth in Chapter 1.

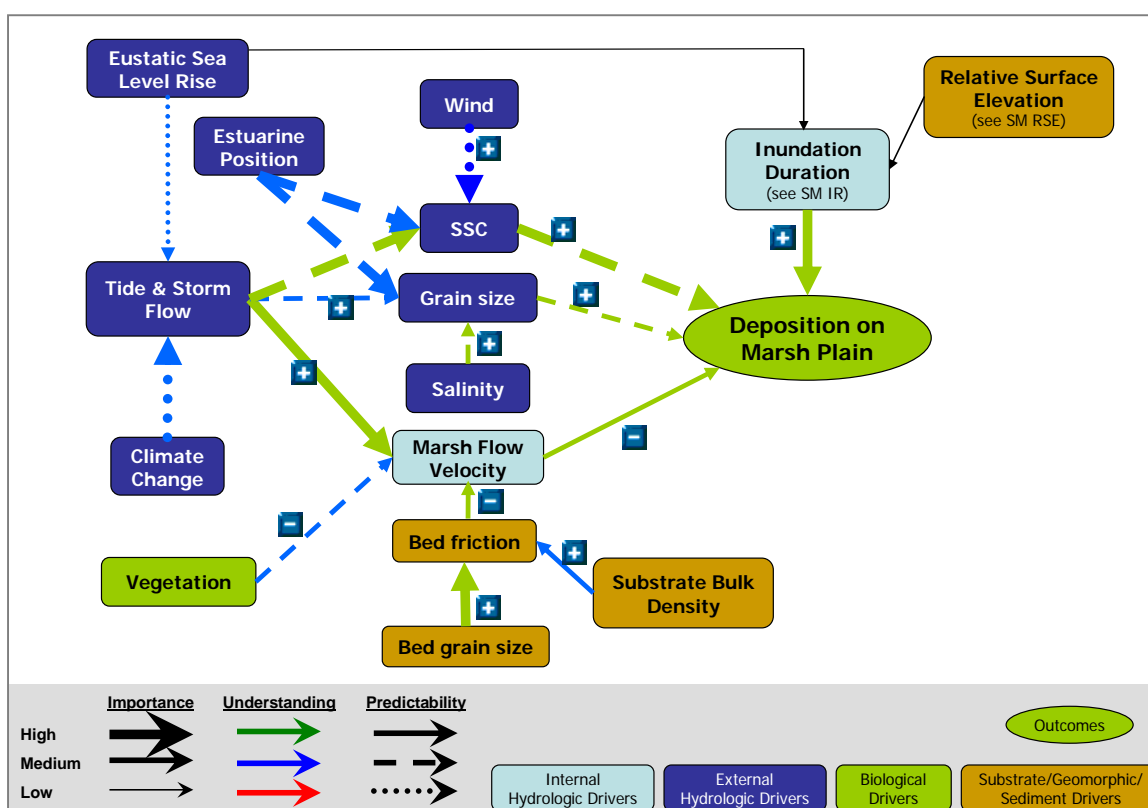


Figure 3-10. Deposition Conceptual Model

Below Ground Biomass Production

Below ground biomass production refers to the production of root and rhizominous material by plants. In saline and brackish marshes, production can be significant (root:shoot ratios >1) as plants may attempt to compensate for poor soil conditions by storing carbohydrates and/or sugars in the roots (Mitsch and Gosselink 2000). The production of below ground biomass can also affect the surface elevation of the marsh plain by causing soil expansion.

There are several abiotic factors that influence below-ground biomass production, including substrate material, soil moisture, water depth, salinity, and nutrient availability (**Figure 3-11**). Available substrate material available is one of the characteristics that determines the suitability of the site for colonization by plants. In Suisun Marsh, most of the substrate material is silts and clays (Conomos and Peterson 1997) which is easily colonized by vegetation if other conditions are acceptable. The inundation regime controls many factors that influence biomass production. The regular inundation of the marsh controls the soil moisture and water depth, which then in turn controls which species of vegetation can grow in a given area based on their tolerance to inundation. The “tidal subsidy” hypothesis (Odum 1980) states that the tides influence marsh vegetation growth by (1) flushing salts off of the marsh plain so they do not accumulate to toxic levels and (2) transporting nutrients into the marsh that stimulate plant growth. Salinity has a significant effect on biomass production because it determines which plants can grow in a given location based on their salt tolerance. Elevated salinities will inhibit plant growth, even for salt-tolerant species, because plants must expend extra energy to overcome osmotic differences (Mitsch and Gosselink 2000). Salinity levels can also affect the distribution of below-ground structures, with more saline conditions favoring less smaller plants with smaller root and rhizome systems and more brackish conditions favoring larger plants with larger root and rhizome systems (Whigham et al. 1989). The important nutrients for plant growth are primarily nitrogen, phosphorus, and iron (Mitsch and Gosselink 2000) which can come from various sources within and outside Suisun Marsh. Nutrient availability is also influenced by the substrate parent material; for example, the relatively lower proportion of cellulose in cattail (*Typha* spp.) relative to bulrush (*Schoenoplectus* spp.) results in relatively faster decomposition rates, which increases the relative availability of nitrogen and carbon from these plants (Hume et al. 2002).

There are also several biotic drivers that influence below-ground biomass production. Individual species will allocate biomass in the roots and shoots at different ratios. Perennial plants in mature tidal freshwater marshes have root:shoot ratios far exceeding 1, indicating that a significant portion of the biomass is below ground, while high-marsh annual plant assemblages generally display root:shoot ratios < 1 (Mitsch and Gosselink 2000). Common fresh and brackish marsh species such as *Bolboschoenus maritimus* and *Schoenoplectus americanus* allocate almost 70% of their biomass to below-ground structures (Karagatzides and Hutchinson 1991), while the below-ground biomass of *Typha latifolia* stands is generally only 40-50% of the aboveground biomass (Sharma and Pradhan 1983). Competition between plants for resources in a marsh will alter the community composition, thereby affecting the below-ground biomass production. If plants with root:shoot ratios >1 dominate there will be significantly more below-ground biomass than if plants with root:shoot ratios <1 dominate.

Herbivory upon underground root structures by birds (e.g. ducks) and mammals (e.g. nutria and muskrats) is common (Mitsch and Gosselink 2000), however it may only account for the consumption of 10-40% of total plant production (Odum 1988). Decomposition by microbial activity is the major pathway by which organic matter is removed from the system and mineralized into inorganic nutrients. Temperature is the most important driver controlling decomposition; the greater the temperature, the faster the decay rate (Mitsch and Gosselink 2000). Soil anoxia is another major driver of decomposition as lower oxygen levels

slow the decay rate. Soil anoxia is primarily influenced by the inundation regime and sediment grain size. When soils are inundated with water they quickly become anoxic; therefore in conjunction with soil permeability, the frequency and duration of inundation will greatly determine the oxygen content of the soil. Grain size is an important factor because pore space generally increases with grain size. Oxygen can diffuse more rapidly through soil with large pore spaces than soil with small pore spaces.

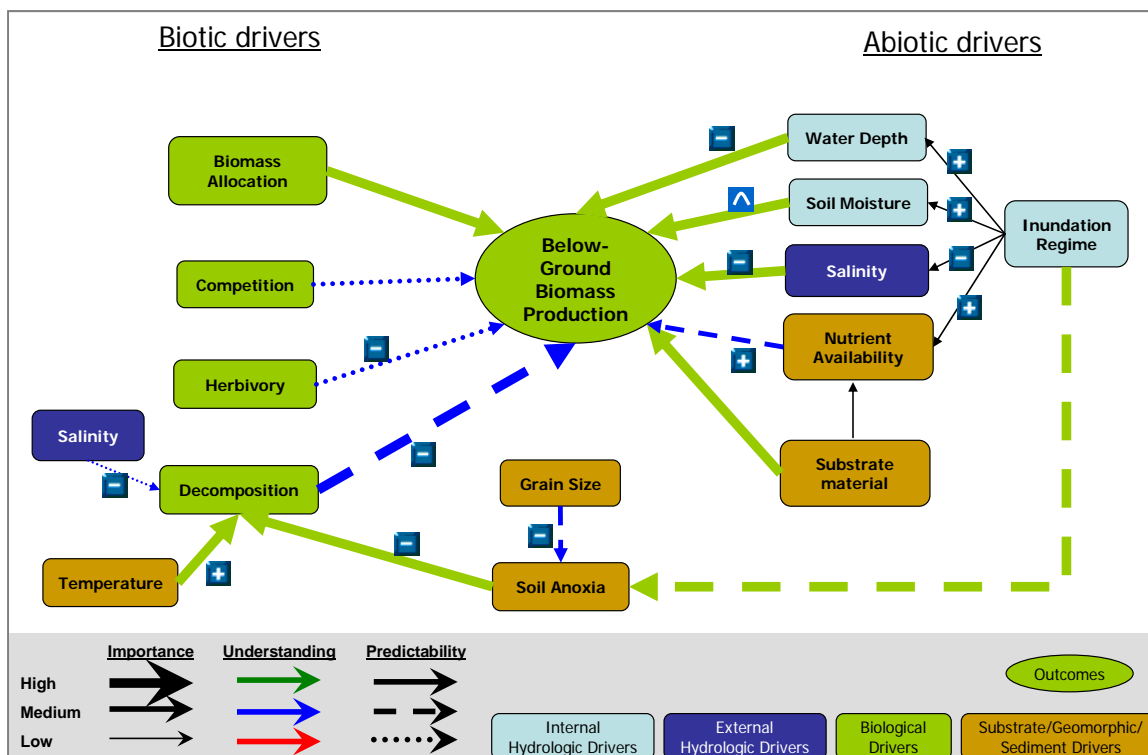


Figure 3-11. Below-Ground Biomass Production Conceptual Model

Peat Accumulation

Peat accumulation refers to the deposition of organic matter on the marsh plain surface. Most of this organic material is autochthonous, and accrues from the deposition of dead plant material from marsh vegetation, but some material is imported from sources outside the marsh. The accumulation of peat can cause a significant increase in marsh surface elevations.

In-situ above-ground biomass production is the main pathway by which peat material is generated. The model for this pathway (**Figure 3-12**) is identical to that for below-ground biomass production (SM BGBP) except that it describes above-ground production. The other driver contributing to peat accumulation is organic matter imported from sources outside the marsh. These sources could include other nearby marshes, bays, upstream watersheds, and the Delta. This organic matter is brought to the marsh by tides and fluvial action. Once the organic matter is brought to the marsh it can be deposited on the marsh plain along with the in-situ organic matter.

The two major drivers that remove organic matter from the system are decomposition and export. Decomposition follows the same pathway as outlined for decomposition of below-ground biomass (SM BGBM) and is the most important driver responsible for the loss of organic material from the system. Export of material due to tidal and fluvial/storm action is also important, but it is more irregular, more difficult to predict, and less understood.

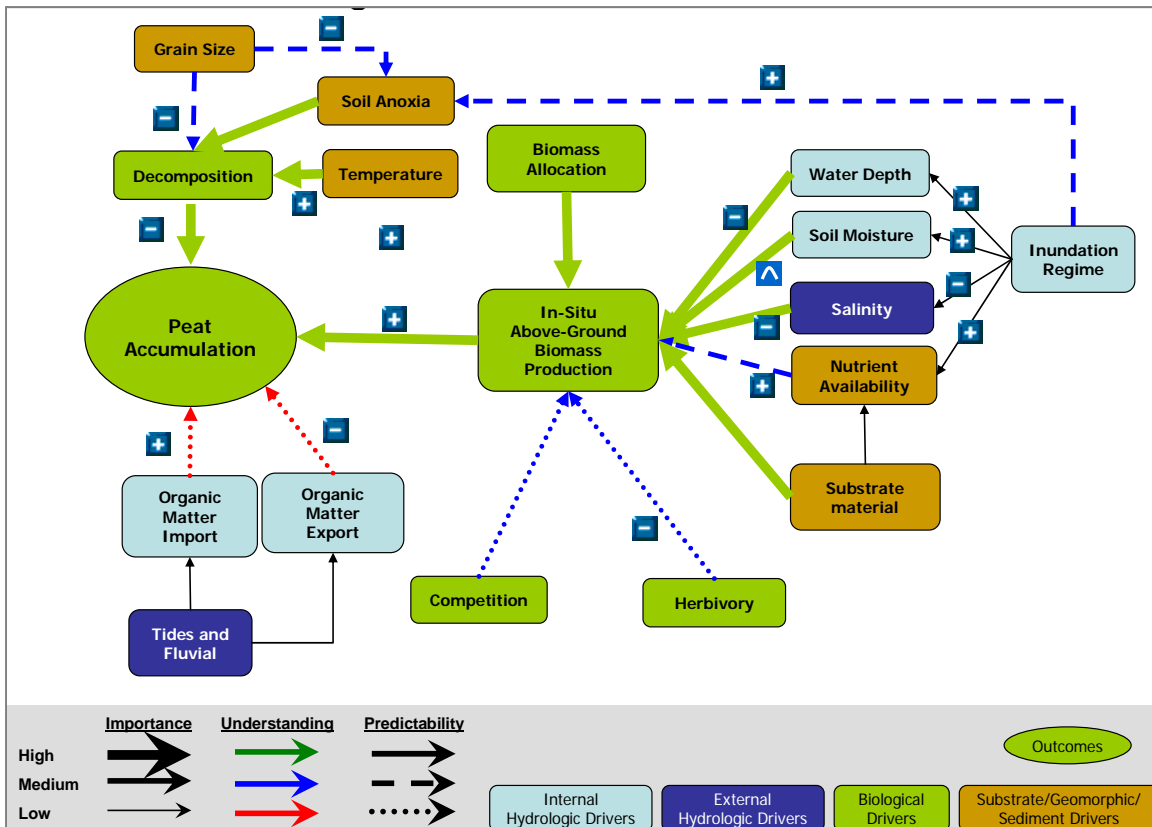


Figure 3-12. Peat Accumulation Conceptual Model

3.2.5 Vegetation as an Ecological Engineer

[Material to be transferred in from IRWM documents]

3.2.6 Geomorphic Evolution in Restored Tidal Marshes (SM GE)

Geomorphic evolution in restored marshes is a complex process dependent upon several different factors; this process can follow alternate trajectories depending on the interactions between these factors. The main features of interest in site geomorphology are the development of the marsh plain, channel network, pannes and ponds, and marsh edges (Figure 3-13).

The antecedent geomorphology sets the stage for the geomorphic evolution of the site as it establishes the existing elevations, substrate material, and degrees of subsidence, compaction, and desiccation. These

conditions will determine where along the continuum of marsh ecological development (shallow subtidal, low intertidal, low/high marsh, etc.) restoration at the site will commence, and to a certain extent how marsh geomorphology will evolve. For example, the existing elevations will determine the baseline inundation regime of a given site. The inundation regime in turn influences most of the processes that drive marsh geomorphic evolution.

The development of the marsh plain is driven chiefly by sediment deposition (SM D) and organic matter accrual through below-ground biomass production (SM BGBP) and peat accumulation (SM PA). In restored marshes in which a levee is breached to allow tidal access, the breach position can have a significant impact on the development of the marsh plain by affecting the availability of suspended sediment and flood velocities across the site. As marshes begin to evolve from their antecedent geomorphology, sediments will begin to deposit on the marsh plain in a manner governed by the initial inundation regime. As sediment deposits on the marsh plain and site elevations rise, the tidal prism above the marsh plain gradually decreases, resulting in a gradual decrease in sedimentation rates. Alternatively, site elevation can be artificially raised by addition of dredge material. In either case, as sediment accumulates, areas of mudflats form. Biological stabilization of the mudflat surfaces by microalgae that secrete mucus may be required for establishment of vascular plants (Adams 1990). Once site elevations reach elevations that are capable of supporting vegetation, and there is a proximal vegetation population source (seed or rhizomatous growth from levee edges), vegetation will begin to colonize the site. The suite of species that colonize a given site is dependent on many factors, such as (1) the location of the site in the estuarine salinity gradient, 2) whether or not colonization is from the lateral expansion of existing vegetation or from “pioneer” (seed) colonization, and (3) habitat connectivity between local plant source populations and the restoration site. In Suisun Marsh, the most common early colonizers will be *Typha* and *Bolboschoenus/Schoenoplectus* species. This vegetation will produce below-ground biomass and above-ground biomass, which later contributes to peat production, thereby further increasing marsh plain elevations. As vegetation spreads across the site, the increased surface roughness of the marsh plain will result in increased rates of sedimentation (relative to rates above bare mud). As site elevations continue to increase, flood-tolerant species will gradually be outcompeted, and the vegetation community will evolve to support more high marsh species. The pioneer colonization of marsh grasses requires sufficient elevation and a shoreline that is protected from wind wave disturbance (Friedrichs and Perry 2001; Williams 2001).

As the marsh plain evolves, it will generally form channel networks. This process is facilitated by differential sediment accretion, when flow concentrates in slight topographic depressions forming channels. The location of channels is often driven by existing terrestrial drainage channels, constraints of underlying bedrock, and previously incised channels in tidal flats or shallow lagoons. In the case of restoration of a historic subsided marsh, remnant tidal marsh plain channels also influence new channel formation. Marsh plain development continues outside these incipient channels through sediment deposition and biomass production, causing the channel banks to build vertically upward, further concentrating flow in the forming channel and becoming more defined as the vegetation establishes (Williams and Orr 2002; Friedrichs and Perry 2001). As the overall elevation of the system continues to rise, these incipient channels continue to

scour headward and along tributary paths, thereby extending the network (Knighton et al. 1992). Because the flow in these tidal channels is bi-directional, they tend to remain fairly stable and do not meander as streams subject to uni-directional flow do (Mitsch and Gosselink 2000). When a marsh channel overflows its banks, water velocities drop and coarse-grained sediments deposit near the channel edge forming a slightly elevated channel-bank levee. This levee is typically a zone of dense vegetation and higher productivity compared with the remainder of the marsh due to slightly higher elevations, nutrient inputs, and better drainage (Mitsch and Gosselink 2000). The dense marsh vegetation causes channels to be deep and narrow and subjected to undercutting and slumping. Slumping appears to be the primary mechanism for lateral migration of tidal channels in south San Francisco Bay (Zedler and Callaway 2001). The combination of slumping and dense vegetation results in tight meander bends in marsh plain channels.

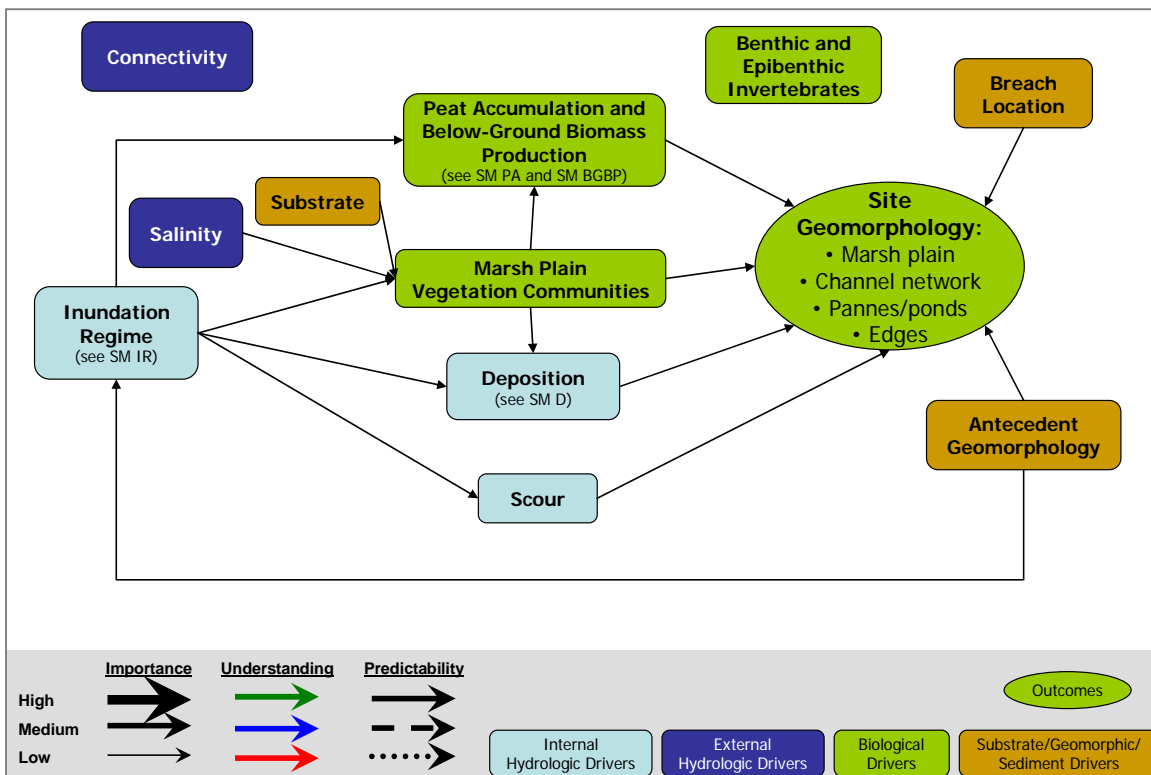


Figure 3-13. Geomorphic Evolution in Restored Tidal Marshes Conceptual Model

Varying patterns of sediment deposition and vegetation growth can also lead to the development of ponds and pannes on the marsh plain. These are hydraulically isolated, intertidal features that retain water even at low tide and are often devoid of vascular vegetation due to the depth of submergence and/or elevated salinities (Mitsch and Gosselink 2000). Shifting patterns of sediment deposition and biomass production can cause these features to form and fill in various locations around the marsh over time. More permanent features can form in areas where free tidal exchange is blocked (Mitsch and Gosselink 2000). In these areas, sediments are not regularly supplied and salinities can become elevated, causing vegetation die-

back. Without the elevation-building drivers of biomass production and sedimentation, subsidence and decomposition can reduce elevations, causing permanent depressions.

3.3 Evolution of Ecological Functions at Restored Marshes

[This section requires further revision]

3.3.1 Habitat Connectivity: Conceptual Model of Restoration Sites at Larger Spatial Scales

Outcomes of tidal marsh restorations depend on the degree to which natural tidal marsh processes are rehabilitated. An additional emerging understanding is that the regional carrying capacity of marsh systems can be enhanced by considering the hydrologic connectivity of functionally variable habitats within the system (Polis et al. 1997). In particular, the rate at which habitats exchange water, solutes, and biota between each other determines the overall primary and secondary productivity rate of the marsh.

Recent literature suggests there is potential for synergy between otherwise fragmented and noncontiguous habitats, where excess production in one can be transported and utilized in the other. For example, Cloern (2007) presents results of a simple two-box model where one box is a high productivity shallow habitat (something like a slough draining a tidal marsh) and the other box is a low-productivity deep habitat (like diked portions of Montezuma or Suisun sloughs). Suisun Marsh has high concentrations of suspended sediment from river inputs and wind/wave resuspension, and algal growth rates are limited by low availability of sunlight energy (Cloern 1999). Light limitation is most severe in deeper channels where algal respiration can balance or exceed photosynthesis. Most of the volume in the larger Suisun Marsh sloughs (e.g. Montezuma Slough, Suisun Slough) is below the photic zone and thus exhibits productivity deficits. Simulations show that total system primary and secondary production (the sum of production in both habitats) varies with the hydrologic connectivity rate between habitats. When the connectivity rate is optimized, productivity exports from shallow donor habitats subsidize production in resource deficit habitats like deeper sloughs. In general, the optimal connectivity rate occurs when the percentage of water mass exchanged per day is roughly equal to the percentage of excess primary production. For example, when a shallow water habitat produces 10% more phytoplankton than it consumes and a nearby heterotrophic habitat is exposed to about 10% of the shallow habitat water volume, then overall primary and secondary biomass is roughly maximized.

The model also explains why consumers like amphipods and copepods have a limit to the amount of food they can take in daily. If the food supply (e.g. phytoplankton biomass) exceeds consumption capacity, then secondary production is limited by feeding constraints of the consumers and reaches a plateau. If some of the excess food supply is exported to low productivity habitats (like Montezuma Slough), then it can support additional secondary production. At the same time, low productivity habitats regenerate nutrients through excess respiration that can in turn be transported to autotrophic habitats, thereby stimulating higher total system primary productivity.

Habitat connectivity rate

The overall system productivity enhancement presented in this conceptual model depends on the relative proximity of high and low productivity habitats. "Connectivity rate" refers to the percentage of water, solutes, and biota mass exchanged between habitats per tidal cycle, calendar day, or spring-neap cycle. The ecology literature generally refers to exchange at the daily timescale since photosynthesis is a daily phenomenon. An additional factor is that phytoplankton production requires some finite time to reach maximum biomass after which it is self-limiting due to reduction of light penetration or consumption of available nutrients. Some new tidal marsh restoration projects (such as Blacklock) might require several days to achieve self-limiting primary biomass production.

Tidal action provides the energy that connects high and low productivity habitats. The key transport process is the tidal excursion, or the distance water parcels travel on each half-tidal cycle. Most of the tidal variability is exhibited at the tidal timescale (approximately 2 times per day) as ebb and flood currents. Another important mode of variability is the spring-neap cycle that generates relatively more or less powerful tides each fortnight. Tidal excursion during spring tides can be much longer than neap tides (and thus higher habitat connectivity rate). Moreover, spring tides are associated with more complete estuary drainage such that more of the volume of a shallow water habitat area will be exported on each half tide. The residence time of water mass in any one habitat is directly related to tidal strength.

A simple conceptual model of this idea is exhibited in **Figure 3-14**. The deep slough on the left-hand side represents Montezuma or Suisun Slough-- generally deep, heterotrophic and, on balance, respiration exceeds production at least part of the time. Alternative tidal marsh restorations are depicted along the tidal creek system (1, 2 and 3). Residence time increases from near zero at the mouth to months at the slough head. Habitat connectivity rate - nominally the inverse of residence time - decreases with distance from the mouth. The hypothetical restoration sites arrayed along the tidal slough axis would exchange water with the deep slough very differently. In this example, sites one and three may be too near and too far, respectively, to match exchange rate with restoration area productivity. Site two may conceptually optimize exchange, and thus overall system productivity.

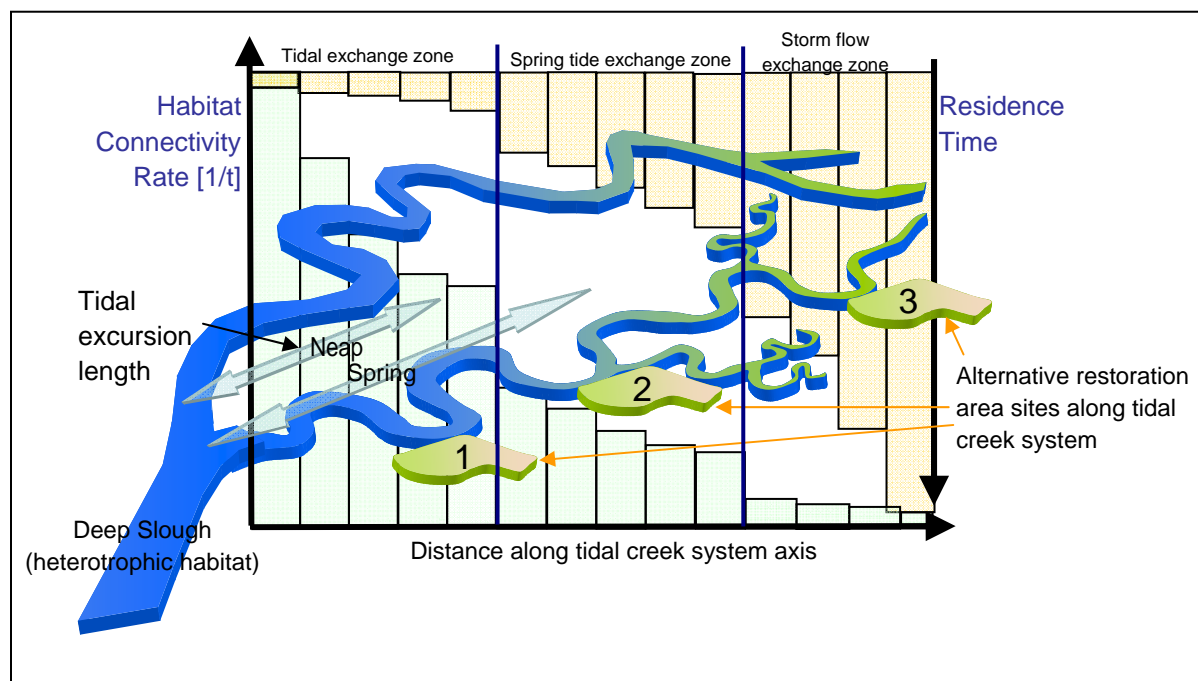


Figure 3-14. Conceptual Model of Habitat Connectivity Between Heterotrophic and Autotrophic Habitats

Left y-axis is habitat connectivity rate, right y-axis is residence time. X-axis is distance from low productivity heterotrophic habitat. Alternative restoration projects sites (1, 2, and 3) would exhibit differential exchange and overall primary and secondary productivity between the site and the deep slough. Source: Enright (DWR)

Research in residence time and habitat connectivity

Hydrodynamic field studies and modeling should be used in tandem to determine transport time scales. Recent literature demonstrates how particle tracking models can be used to parameterize residence time, exposure time, and/or flushing rate (Monsen et al. 2005). Model grids must be of adequately fine resolution to resolve at least lateral and longitudinal mixing, especially at channel junctions. Where density currents are strong, fully three-dimensional models may be required. Oceanographic equipment for hydrodynamic field studies must be deployed in a fashion that adequately integrates channel cross sections at various time scales. This has proven to be a difficult task (Jay et al. 1997) though equipment and procedure improvements offer hope for accuracy that is sufficient for restoration project siting (Dinehart et al. in prep). An extremely useful product of the field hydrodynamic measurement and modeling collaboration would be isopleth maps showing indexes of habitat connectivity at spatial objects. With such a map, planners would be able to locate those landscapes that are most likely to optimally exchange their water mass with nearby heterotrophic channels to achieve enhanced primary and secondary production.

3.3.2 General Ecological Functions Conceptual Model

Higher trophic level organisms derive ecological functions from tidal marsh in many different manners depending on the species considered. Here we describe the general suite of parameters that affect ecological functions. **Figure 3-15** illustrates the general conceptual model for ecological functions at higher trophic levels. Several physical processes and conditions affect ecological functions: marsh geomorphology, marsh elevation, inundation regime, substrate, salinity, and connectivity. Three biological communities affect functions at higher trophic levels: marsh plain vegetation community, invertebrates (benthic, epibenthic, aquatic, and terrestrial), and other primary producers (attached algae, phytoplankton, submerged aquatic vegetation [SAV], and floating aquatic vegetation [FAV]). Interactions between different physical processes determines the composition of the tidal marsh vegetative community, the type of invertebrate community, and the suite of non-emergent primary producers.

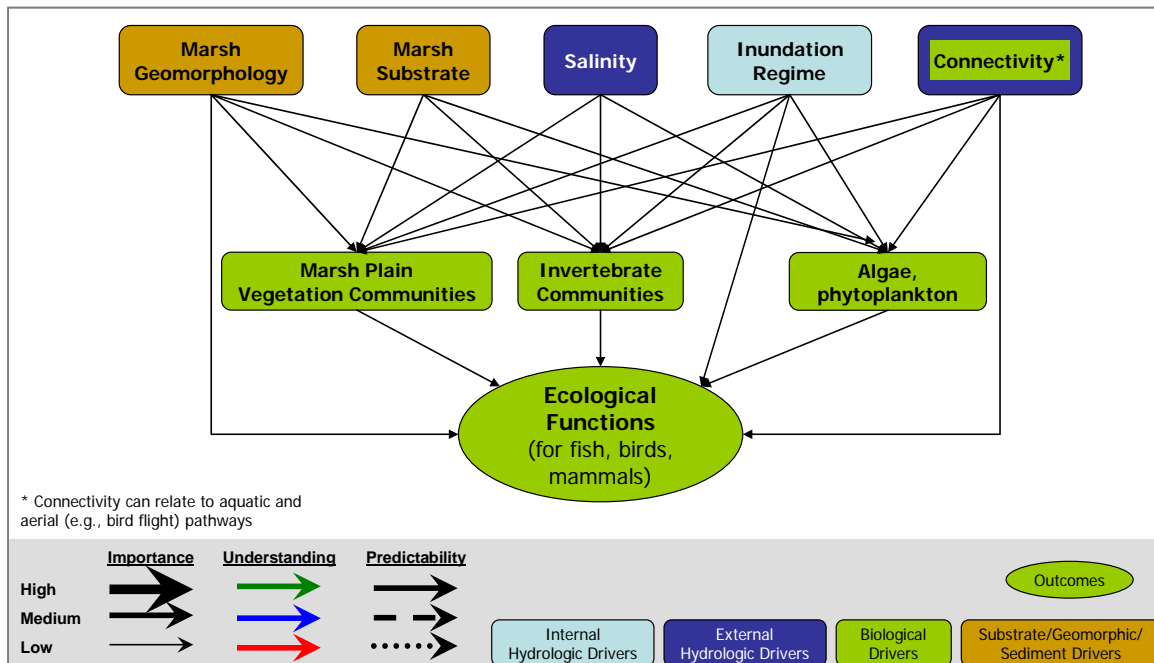


Figure 3-15. General Higher Trophic Level Ecological Functions Conceptual Model

3.3.3 Substrate Characteristics (SM SC)

Substrate characteristics can exert a significant influence on marsh ecology. Marsh substrate serves as the primary storage location of important nutrients for marsh vegetation and it is the location where most chemical transformations take place (Mitsch and Gosselink 2000). The main substrate characteristics of concern are grain size, organic and inorganic matter content, bulk density, soil chemistry, and permeability. These characteristics are affected by several drivers, both biotic and abiotic (**Figure 3-16**).

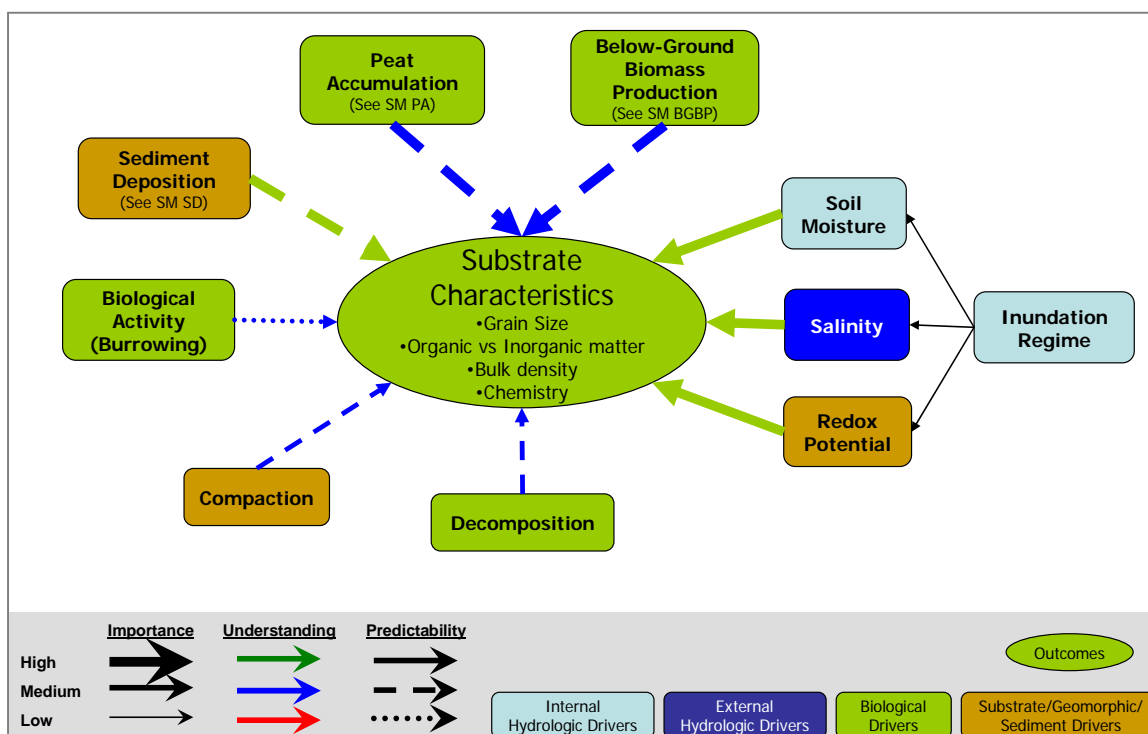


Figure 3-16. Substrate Characteristics Conceptual Model

Substrate characteristics, such as substrate particle size, reflect current velocities in the area. Slower currents are represented by finer silt, clay and organic detritus, while faster currents are composed primarily of coarser sand and gravel. The organic matter content of the substrate is primarily influenced by peat accumulation (SM PA) and below-ground biomass production (SM BGBP), while the inorganic matter content is driven by sediment deposition (SM SD). Substrate grain size (inorganic material) is influenced by sediment deposition patterns and the geology of source sediment. The bulk density of the soil describes the mass per unit volume (g/cm^3). Generally, soils with a higher organic matter content will have lower bulk densities due to their high porosities, or percentage of pore space per unit volume (Mitsch and Gosselink 2000). The IRWM project measured soil bulk density in five marshes across a salinity gradient in San Pablo Bay and Suisun Bay. The soil in Browns Island, an “ancient” marsh in eastern Suisun Marsh near the border of the Delta, has a bulk density of around $0.25 \text{ g}/\text{cm}^3$, which is considerably lower than that of the more saline natural marshes to the west (0.48 to $0.57 \text{ g}/\text{cm}^3$); although the site’s relative lack of disturbance by humans and location at the high-energy confluence of the Sacramento and San Joaquin rivers may also play important roles in governing substrate characteristics (IRWM 2006). Generally, marshes with high biomass production and low sediment deposition should have lower bulk densities than marshes with low biomass production and high sediment deposition. The soil bulk density is impacted by compaction and decomposition, both of which act to increase bulk density. Compaction is a physical process that increases the mass per unit volume as substrate settles and dewateres over long periods of time. Decomposition causes a reduction in the size of organic matter particles (and in some cases transforms portions of organic molecules into gases that then escape the substrate completely), thus reducing the pore spaces and

increasing bulk density. When inundation of highly organic, low-bulk-density marsh soils is prevented by activities such as diking and draining, the high porosity of these soils makes them susceptible to subsidence from compaction and the conversion (decomposition) of organic material to gases such as carbon dioxide (CO₂) and methane (CH₄). More mineral marsh soils are less susceptible to subsidence, but can still demonstrate subsidence levels that would move relative surface elevations well below the tidal frame, presenting a challenge to restoration (for more information about subsidence, see Section 1.10). Bulk density can also be impacted by animal activity. Burrowing by organisms such as worms, crayfish, insect larvae, and small mammals increases pore space and thus decreases bulk density.

Soil chemistry is also affected by several factors. Soil moisture, which is largely controlled by the inundation regime, will have a large effect on the availability of oxygen in the substrate. Soils saturated with water can quickly become anoxic, preventing plants from performing normal aerobic root respiration and affecting the composition and availability of nutrients in the soil (Mitsch and Gosselink 2000). As a result, the vegetation community will only include plants with specific adaptations to such conditions. Similarly, anoxic soil conditions will change the oxidation-reduction (redox) potential of the substrate. Under anaerobic conditions the redox potential will drop and lead to a series of reactions that will alter soil chemistry and nutrient availability (Mitsch and Gosselink 2000). Under anaerobic (reducing) conditions, nitrate is reduced to nitrite and ultimately gaseous nitrogen, ferric iron is reduced to ferrous iron, and sulfur compounds are reduced to sulfides. These reduced compounds can then interact with a variety of compounds, especially metals such as copper and mercury (see Chapter 1). All of these transformations change the bioavailability of nutrients and other compounds for plants and microorganisms. The nutrient availability also depends on the organic versus inorganic matter content of the substrate. Much of the available fertility of peat soils in marsh systems may be invested in existing plant layers or bound up by anoxic soil conditions.

The pH of wetland substrate is dependent on several factors. Soils with high organic matter content are generally acidic, while mineral soils are more neutral or alkaline. The pH can also be influenced by soil moisture, redox potential, and iron content (Mitsch and Gosselink 2000). Substrate pH can have an effect on many biological processes and can alter the availability of nutrients for plant growth.

Substrate salinity is regulated by the inundation regime and the temporally variable salinity of source waters. Salinity has a significant effect on marsh ecology by selecting for plants with ecological adaptations to saline environments. Salinity can also indirectly influence some chemical transformations in the substrate; for example, rates of methane production are generally higher in saline soils due to the abundance of sulfate (Mitsch and Gosselink 2000).

3.3.4 Invertebrates

Invertebrates that may occupy tidal marshes include terrestrial invertebrates, as well as aquatic benthic invertebrates that reside in the sediment (infauna) and on the surface of the sediment or other substrate (epifauna). The distribution of aquatic benthic invertebrates is influenced by a variety of factors including salinity, substrate composition and current velocity (Markmann 1986, Nichols and Pamatmat 1988). Salinity

is the primary factor influencing aquatic benthic invertebrate communities. Low salinity conditions generally correlate to low diversity and abundance, and few species are able to tolerate high fluctuations in levels of salinity (Markmann 1986, Nichols and Pamatmat 1988). For example, Grizzly and Suisun Bay are exposed to extreme salinity variations and typically support fewer species and lower densities compared to areas with more established salinity regimes in the San Francisco Bay-Delta (Markmann 1986). Salinity regime in the Suisun Marsh is largely influenced by freshwater inflows (see Chapter 2) and the salinity control structures within the Marsh (see Chapter 2). Suisun Marsh is situated within the maximum estuarine salinity gradient in the San Francisco Estuary and it generally encompasses the Estuary's low salinity zone.

Current velocities can influence the transport of suspended food resources, displace substrate and disperse plank tonic life stages of some benthic invertebrate species (Nichols and Thompson 1985, Markmann 1986). Sampling from Carquinez Strait through the Delta showed areas with slow to moderate current velocities were able to support a larger and more diverse population of benthic communities (Markmann 1986). Emergent vegetation can slow currents, stabilize sediments and support invertebrate communities by providing nutrients and substrate for attachment (Orth 1977). Faster currents, often found in shallow sediments, can lead to unstable sediments that are not conducive for the settlement of most species (Kimmerer 2004). Physical disturbances can contribute to a state of non-equilibrium in the benthic community and open habitat for opportunistic species, such as non-native, invasive species (Oliver 1977, Nichols 1979).

The abundance of benthic macroinvertebrate populations fluctuates within the year due to reproduction, recruitment and mortality (Nichols and Thompson 1985). Temperature is the key variable regulating growth, metabolism and reproduction of invertebrates (Kimmerer 2004). Monitoring in the San Francisco Bay-Delta have documented a benthic invertebrate population increase in spring and early summer, when water temperature rises above 15°C and the onset of reproduction occurs (Markmann 1986).

There is currently no monitoring data relating to aquatic invertebrate species that utilize tidal marsh habitat within Suisun. However, based on the described factors that influence aquatic invertebrate distribution, we would expect to see variation between tidal channels, marsh plains and ponds within the Marsh. Additionally, these areas will likely be subject to varying inundation regimes and levels of predation, which would further influence the distribution and abundance of tidal marsh invertebrates.

3.3.5 Vegetation Communities

[Material to be inserted from IRWM]

3.4 Resulting Ecological Functions at Stages of Restoration Evolution

Once lands are restored to tidal action, they begin to undergo the process of evolving toward high marsh conditions. The rate of that evolution is controlled by the many factors described in Section 3.3. This section summarizes the ecological functions associated with each evolutionary stage of a marsh restoration, using site elevation as the proxy indicator for inundation regime. **Figure 3-17** illustrates the general nature of the elevation-inundation regime-marsh stage concept. Each of the species accounts in Chapter 4 describes ecological functions for each of these stages.

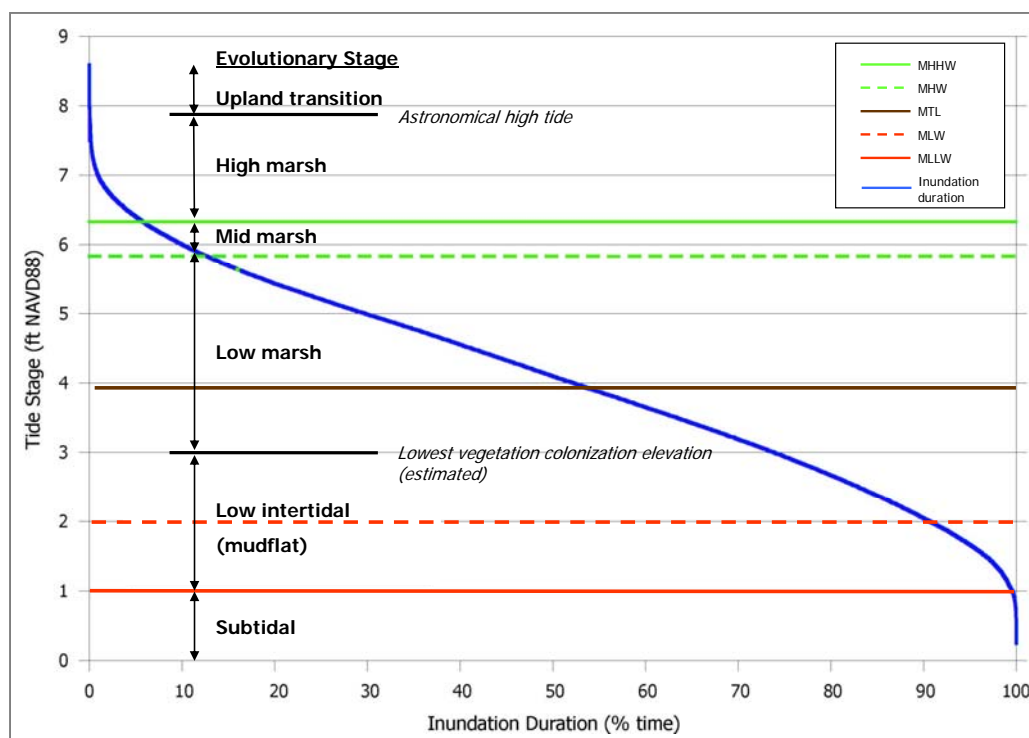


Figure 3-17. Inundation Regime, Marsh Elevation, and Restoration Evolution Trajectories

Subtidal: A site at this evolutionary stage is primarily open water with some fringing vegetation along the adjacent levees. Pelagic primary (phytoplankton + cyanobacteria) and secondary (zooplankton + invertebrates) production provides a food base for aquatic organisms such as fish and benthic organisms such as clams and mussels. SAV or FAV may grow in subtidal areas that remain within the photic zone, supporting the development of both periphyton and invertebrate communities. Fish such as juvenile Chinook salmon, splittail, striped bass, sturgeon, prickly sculpin, threespine stickleback, and tule perch will derive direct benefits via primary and secondary pelagic production within the site, while Delta and longfin smelt will benefit from the export of this production from the site into deeper subtidal receiving waters. For all fish species, access to the site will depend on the inundation regime. For example, larger fish species

will in general require deeper inundation depths than smaller species. As the tides rise and fall, inundation depths will vary across the site, and thus access for different species will vary. The subtidal stage will also provide foraging habitat for a broad range of waterfowl, such as dabbling ducks and wading birds (herons and egrets) in shallow water and diving ducks in deeper water. As with dependent fish species, as tide levels change, the spatial extent of shallow/deep subtidal habitats (and thus the relative amount of habitat for dependent waterfowl) will change.

Low intertidal: At this stage, the site is a mix of shallow open water and intertidal mudflats. Pelagic primary and secondary production continues in shallow open water, as does growth of SAV/FAV and their associated periphyton and invertebrate communities. Intertidal mudflats may directly support communities of periphyton (e.g., filamentous algae), which serves as habitat for a wide range of invertebrates such as midges, flies, and their allies. These invertebrates provide a food base for resident and migratory shorebirds (when exposed) and fish and dabbling ducks (when submerged). As with subtidal habitats, this stage provides direct benefits to aquatic species such as juvenile Chinook salmon, splittail, striped bass, sturgeon, prickly sculpin, threespine stickleback, and tule perch; and indirect benefits via exported pelagic production to Delta and longfin smelt. Wading birds may prey on fish in shallow open water areas. In the western side of Suisun Marsh, sites at this stage may provide marginal foraging habitat for California clapper rails.

Low marsh. As sediment deposition and above- and below-ground biomass production raise site elevations, emergent mudflats grow high enough to support vegetation colonization by low marsh species such as tules (*Schoenoplectus/Bolboschoenus* spp.) and cattail (*Typha* spp.). Like the emergent mudflat before it, this vegetation supports a complex periphyton community that in turn supports robust communities of aquatic and aerial invertebrates. These invertebrates are consumed by fish (when aquatic) and birds and bats (when aerial). A small band of middle marsh vegetation may have established along the upper edges of the site, which would include plants such as saltgrass, pickleweed, salt-marsh dodder, and *Jaumea*. Sinuous tidal channels have formed in the marsh plain with vegetated bank edges. Native fish will use tidal channels during mid to high tides, depending on channel invert elevations, and may use the marsh plain when it's inundated, but are more likely to derive indirect benefits via exported primary and secondary production. Where there is enough cover, salt marsh common yellowthroat and Suisun song sparrow may use the low marsh, although it is likely to be marginal habitat. In the western side of the marsh, California clapper rails may use the low marsh, especially tidal channels, for foraging and refugial habitat. Tidal channels will continue to support benthic invertebrate communities, thereby providing foraging habitat for dabbling ducks and wading birds.

Mid marsh. At this stage the marsh has evolved into a mosaic of intertidal mudflats, low marsh, and middle marsh. Continued sediment deposition and above- and below-ground biomass production have increased marsh plain elevations in certain areas, causing mid-marsh species such as saltgrass, pickleweed, salt-marsh dodder, and *Jaumea* to out-compete low marsh plants such as tules and cattails. The area and volume of periphyton attached to marsh vegetation continues to expand, supporting aquatic

and aerial invertebrates. During high tides the entire marsh plain is flooded, and the only refuge for wildlife is the fringe of upland along the remaining levees. As with low marsh, aquatic species such as splittail, striped bass, and other fish may use the marsh plain when it's inundated, but are more likely to derive indirect benefits via exported primary and secondary production. Fish will continue to use tidal channels as foraging habitat during mid to high tides as long as invert elevations allow access. Suisun song sparrow and Suisun marsh common yellowthroat are likely to use mid-marsh areas providing there is sufficient cover. In the western side of the marsh, California clapper rails may use the mid-marsh and tidal channels for foraging and refugial habitat. California clapper rails may use fringing higher elevation areas for nesting, but this is likely to be marginal habitat. Salt marsh harvest mouse (SMHM) and Suisun shrew are likely to occupy the mid-marsh areas during low tide, as long as there is ready access to fringing higher elevation areas for refuge during high tides. Tidal channels will continue to support benthic invertebrate communities, thereby providing foraging habitat for dabbling ducks and wading birds. The higher elevation mid-marsh plain areas would provide marginal conditions for colonization of the rare plants, including soft bird's beak. Suisun thistle (*Cirsium hydrophilum* var. *hydrophilum*) and Delta tule pea (*Lathyrus jepsonii* ssp. *jepsonii*) may colonize along the channel edges.

High marsh. High marsh ranges from MHHW to the extreme high water line. This elevation provides refuge for wildlife during most tidal cycles, but is occasionally completely inundated by spring tides, storm events, or a combination of the two. Sediment deposition is significantly decreased due to the small tidal prisms that irregularly inundate the marsh plain. Aquatic species primarily benefit from sites at this stage by foraging in inundated tidal channels and by the increased export of primary and secondary production. The entire marsh supports a periphyton community that support aquatic and aerial invertebrates. In the western Marsh, California clapper rails may utilize the sites (especially tidal channels) for foraging, refugial, and nesting habitat. This stage is optimal habitat for Suisun song sparrow, saltmarsh common yellowthroat, SMHM and Suisun shrew, who may utilize the site for foraging, nesting, and high tide refugia. Tidal channels will continue to support benthic invertebrate communities, thereby providing foraging habitat for dabbling ducks and wading birds. Conditions at this stage are optimal for colonization of the rare plant species including soft bird's beak on the marsh plain, and Delta tule pea and Suisun thistle along the channel edges.

Upland transition. Upland transition occurs from high marsh to upland elevations. This zone has the greatest variety of plant species and provides refuge to wildlife during high tides. This habitat provides minimal benefit to aquatic species except as a buffer between potential sources of pollution (such as roads) and wetland/aquatic habitats. In the western side of the marsh, California clapper rail may use the upland transition stage for foraging and refuge, but are not likely to use the site for nesting. This stage would likely provide marginal habitat for Suisun song sparrow and salt marsh common yellowthroat, as both species depend on tall vegetation for cover. SMHM may utilize the site for foraging, nesting, and high tide refugia. Like high marsh, this stage provides optimal conditions for colonization of the rare plant species including soft bird's beak and Suisun thistle.

3.5 Considerations in Restoration

Moving forward with tidal marsh restoration in Suisun Marsh will yield the most effective ecosystem-scale outcomes if a number of important landscape-scale factors are taken into account (Section 3.5.1). From there, the details of screening prospective sites involves considering a wide range of site selection factors (Section 3.5.2). Finally, tidal marsh restoration in Suisun Marsh may benefit from inclusion of the concept of “habitat levees” (Section 3.5.3).

3.5.1 Landscape-Scale Factors in Restoration

First and foremost is to establish ecosystem-level restoration goals. Here we propose two such goals:

- **Goal 1:** conserve and recover native estuarine species and communities including rare and listed species (aquatic and terrestrial)
- **Goal 2:** re-establish natural processes that support other wetland ecosystem services such as food web productivity, flood attenuation, water quality enhancement, carbon sequestration, and recreation

Next, it is important that to achieve the desired ecological outcomes of restoration, more than just physical habitat restoration is needed (**Figure 3-18**):

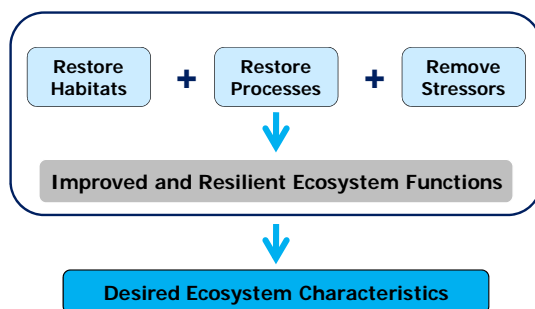


Figure 3-18. The Three Elements of Restoring Desired Ecosystem Characteristics

It is next important to recognize that the native estuarine species for which restoration efforts are geared evolved in a natural estuarine setting complete with significantly greater amount of tidal marshlands (**Figure 3-19**), distribution of those marshlands throughout the estuary, and exposure to fluctuating environmental conditions on time scales ranging from days (tides), weeks (spring-neap tides), seasons, and interannual variation including long cycles of drought and wet.

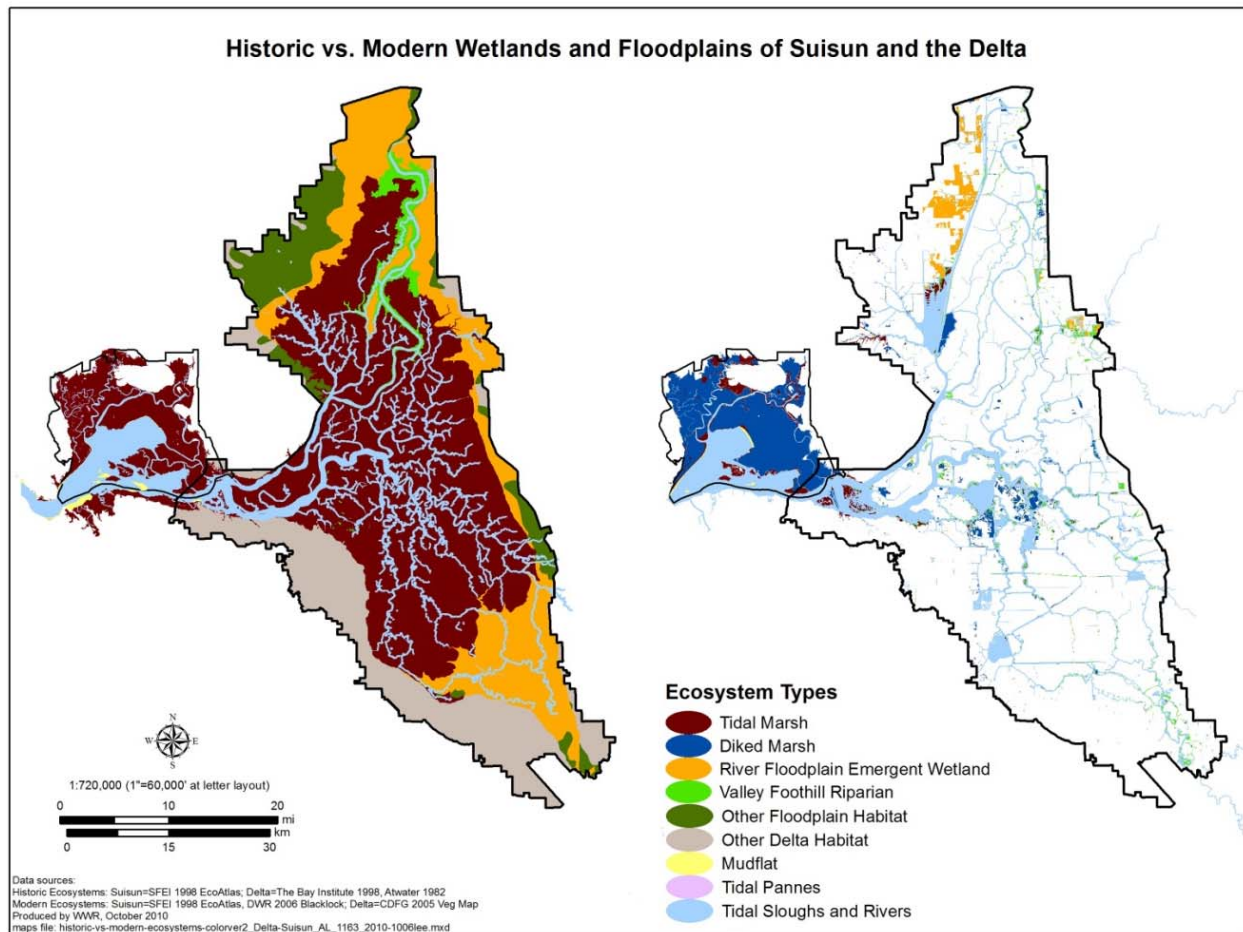


Figure 3-19. Estuarine Habitats of the San Francisco Estuary, Pre-European and Modern

Data sources: historical conditions from TBI 1998 for the Delta, SFEI EcoAtlas for Suisun Marsh. Modern conditions from DFG 2005 vegetation survey data for the Delta and SFEI EcoAtlas for Suisun Marsh, updated to include restoration projects (e.g., Blacklock).

Sea level rise over the long term will require the ability of marshes to move upward and thus landward. This process, known as estuarine transgression, provides the opportunity for the tidal marshes to maintain area as the projections of more rapid sea level rise take place. The nature of the wetland edge – natural, gentle sloped alluvial fans vs. steep terrain vs. hardened edges like levees – all affect the ability of tidal marshes to persist over the long term. **Figure 3-20** provides a schematic of these different configurations and illustrates how Suisun Marsh has some room to accommodate estuarine transgression though its edges are for the most part far more steep than found around the margins of the Delta.

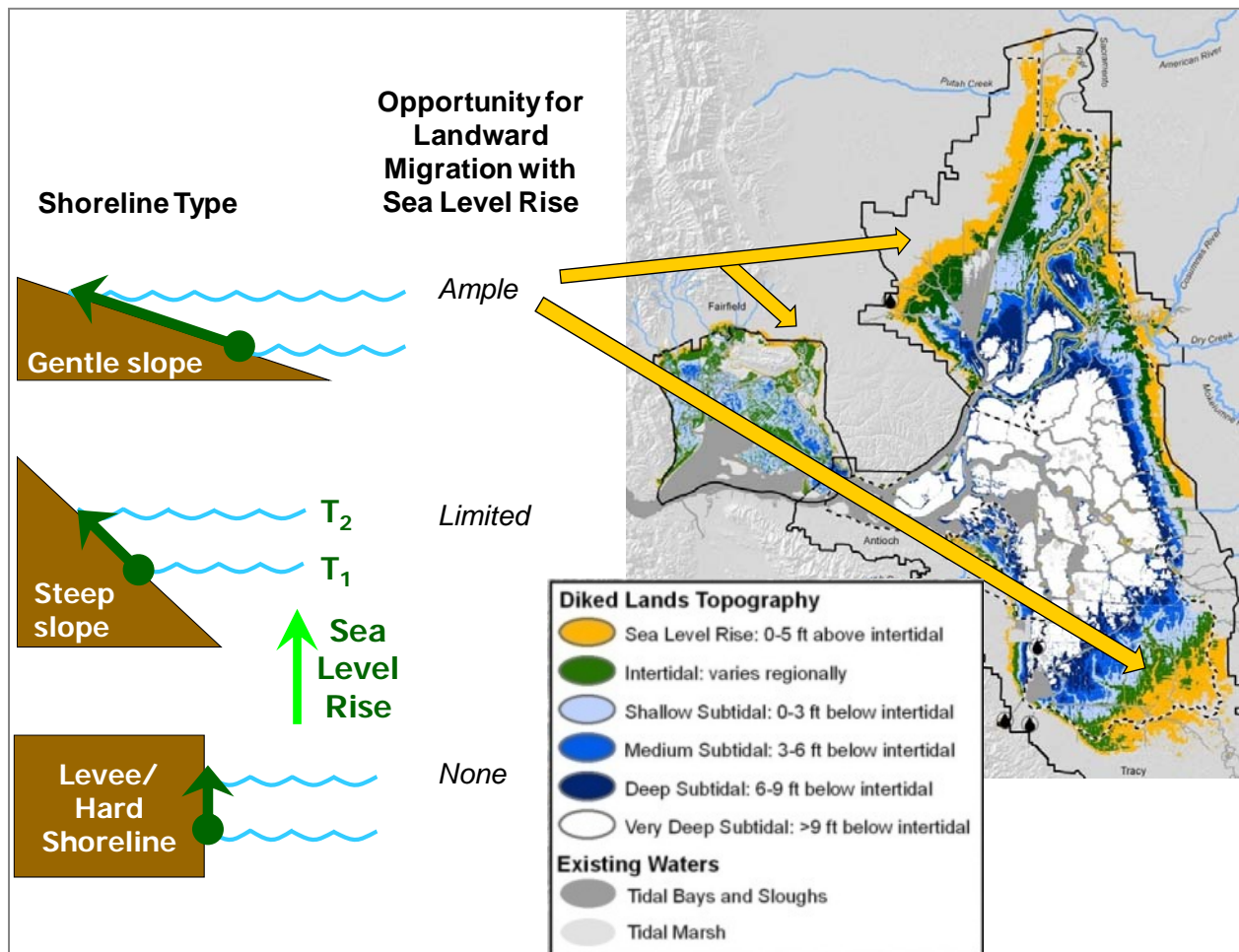


Figure 3-20. Estuarine Transgression and Sea Level Rise

The key hydrodynamic processes and sediment supply regime of Suisun Marsh, discussed in Chapter 1, are also critical factors in large-scale tidal restoration in Suisun Marsh. Of particular import is to consider the general patterns of sediment supply in Suisun Marsh relative to the potential for sedimentation to reverse subsidence.

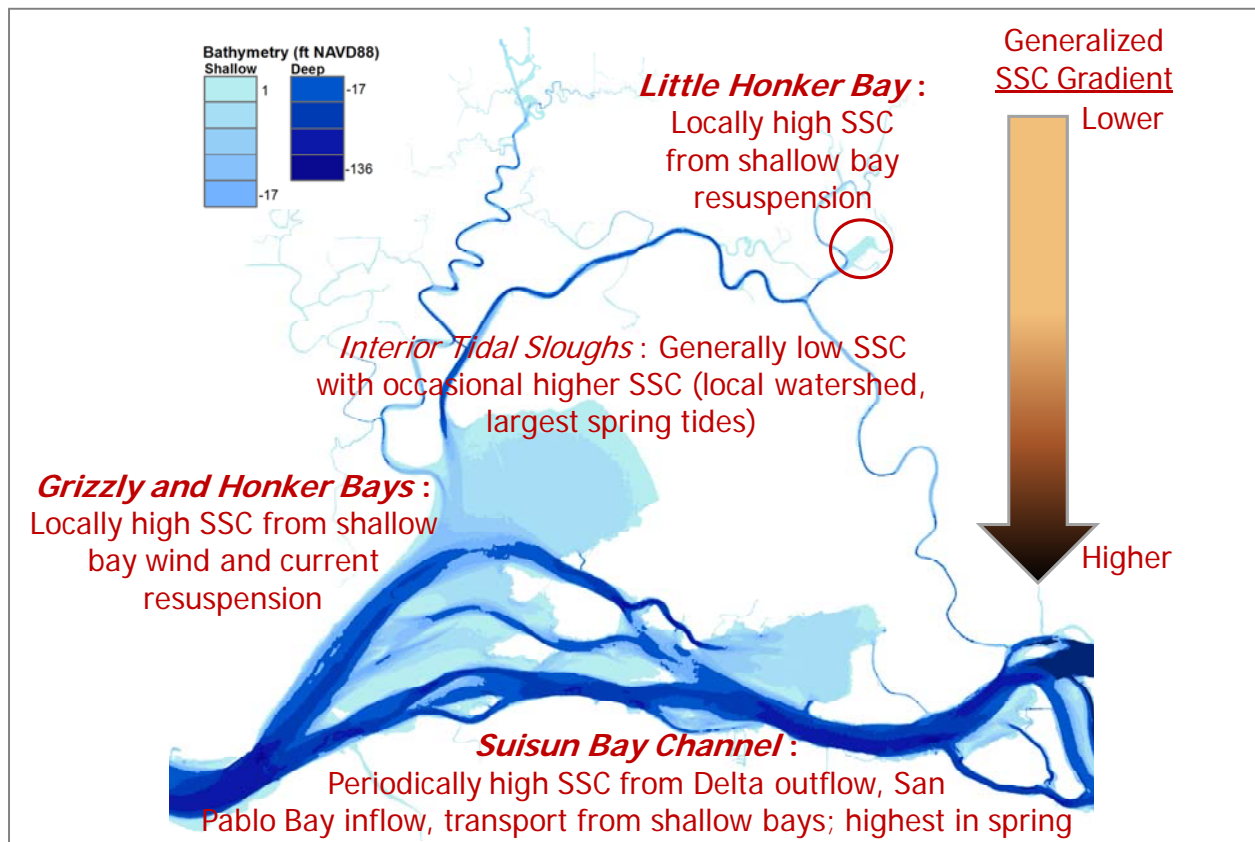


Figure 3-21. Generalized Patterns of Sediment Supply in Suisun Marsh

From those discussions stems the concept of utilizing available tidal energy effectively. Opening diked, subsided lands to the tides increases the total tidal volume of the estuary and affects the distribution of tidal energy. **Figure 3-22** illustrates how restoring the same tidal prism volume at different locations in Suisun Marsh or the Delta affects tides from the Golden Gate to the Delta (figure courtesy of Chris Enright, DWR). As restored sites increase in elevation toward high marsh, their total tidal prism decreases and their effects on tide ranges will decrease over time; i.e., they “give back” their tidal energy as they evolve.

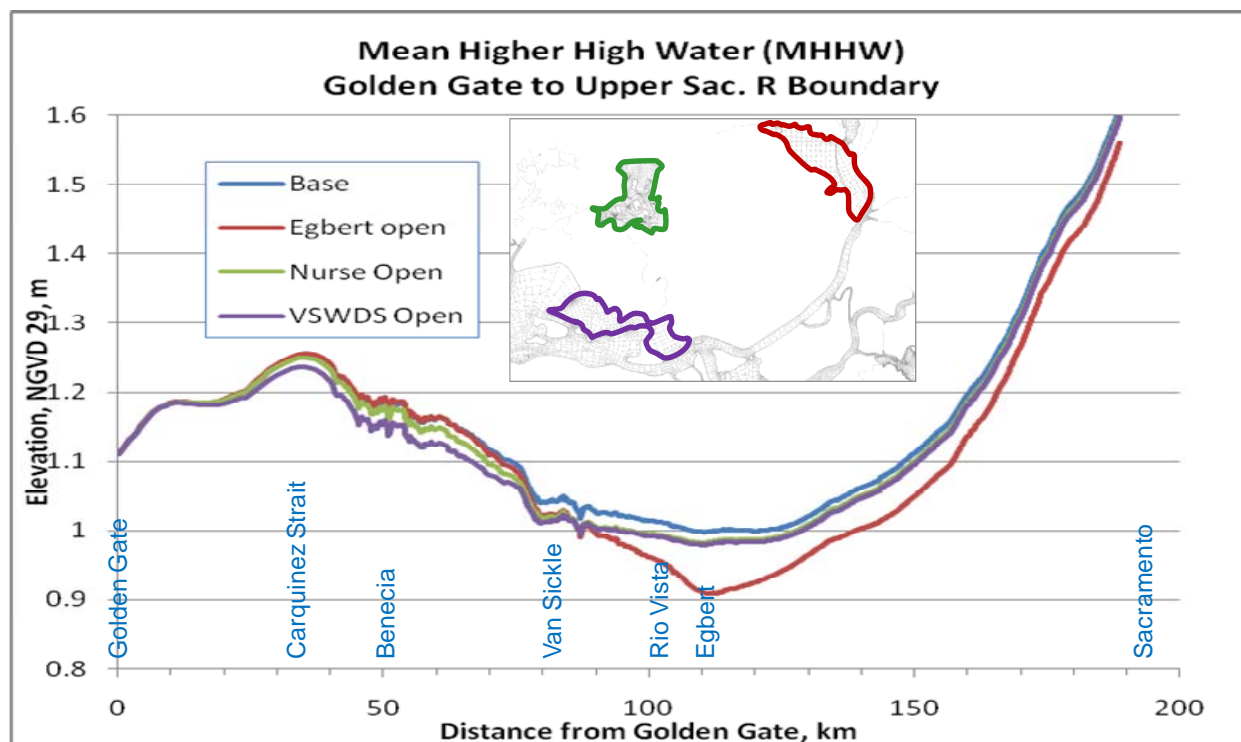


Figure 3-22. Comparison of Effects on the Tides from Different Restoration Locations

Source: Chris Enright, DWR. Figure shows elevation of mean higher high water from the Golden Gate Bridge upstream to Sacramento. Base case is current condition. Egbert is north of Rio Vista. Nurse is northeast Suisun Marsh. VSWDS is Van Sickle and Wheeler Island. All restorations reflect approximately the same total volume of tidal prism added to the estuary.

3.5.2 Site Selection Factors

Selecting where to conduct tidal marsh restoration is both simple and complex. The underlying premise is that certain properties are better suited and more cost-effective for restoration than others. The criteria for site suitability stem directly from all the factors discussed in this Chapter and in Chapter 1. The Suisun Environmental Compliance and Action Team (ECAT) has developed a comprehensive checklist for reviewing property suitability. The core site selection factors are:

- 1) **Land surface elevation** – degree of subsidence
- 2) **Extent of surrounding lands requiring ongoing flood protection** – minimize need for levee maintenance and upgrade requirements
- 3) **Extent to which site contains remnant tidal sloughs that can be “reoccupied”** – ability to restore tidal exchange effectively
- 4) **Position in Suisun** relative to where can best support broad range of target species, best take advantage of sediment supply, and link to adjacent aquatic habitats
- 5) **Size of property** – larger properties provide greater restoration extent

- 6) **Potential for including surrounding properties** – can restoration projects be made larger and in particular through including additional properties can costly constraints be reduced or eliminated
- 7) **Infrastructure impediments** – pipelines, natural gas wells, etc.

3.5.3 Incorporating Habitat Levees

Habitat levees are designed to re-establish facsimiles of marsh topographic gradients. They are low, wide, gently sloping (minimum 7:1 slope), vegetated levees, which may be overtopped during storm surges (where appropriate) with nominal eroding or destabilizing (**Figure 3-23**). Periodic flooding of lower edges of habitat levees may promote dense, tall, high marsh vegetation, which provides cover for resident native marsh wildlife. Expected dense upper marsh vegetation on habitat levees may also reduce the efficiency of predator travel and foraging in adjacent wetlands. Intermittent overtopping by spring tides will flood out terrestrial predator dens (rats, raccoons, skunks, fox) where they are not compatible with local management priorities and endangered species recovery.

Lower crest elevations will also facilitate the dispersal of tidal litter, which is an important natural component of tidal refugial habitat (Johnston 1957). Lower levee crests and gentle, vegetated levee slopes should minimize levee erosion and minimize maintenance requirements. Lower crests will also subside at slower rates than levees capped at higher elevations.

Elimination of the recurrent disturbance cycle associated with dike erosion and maintenance may reduce the competitive advantage of many non-native plants, and native high marsh vegetation may eventually dominate.

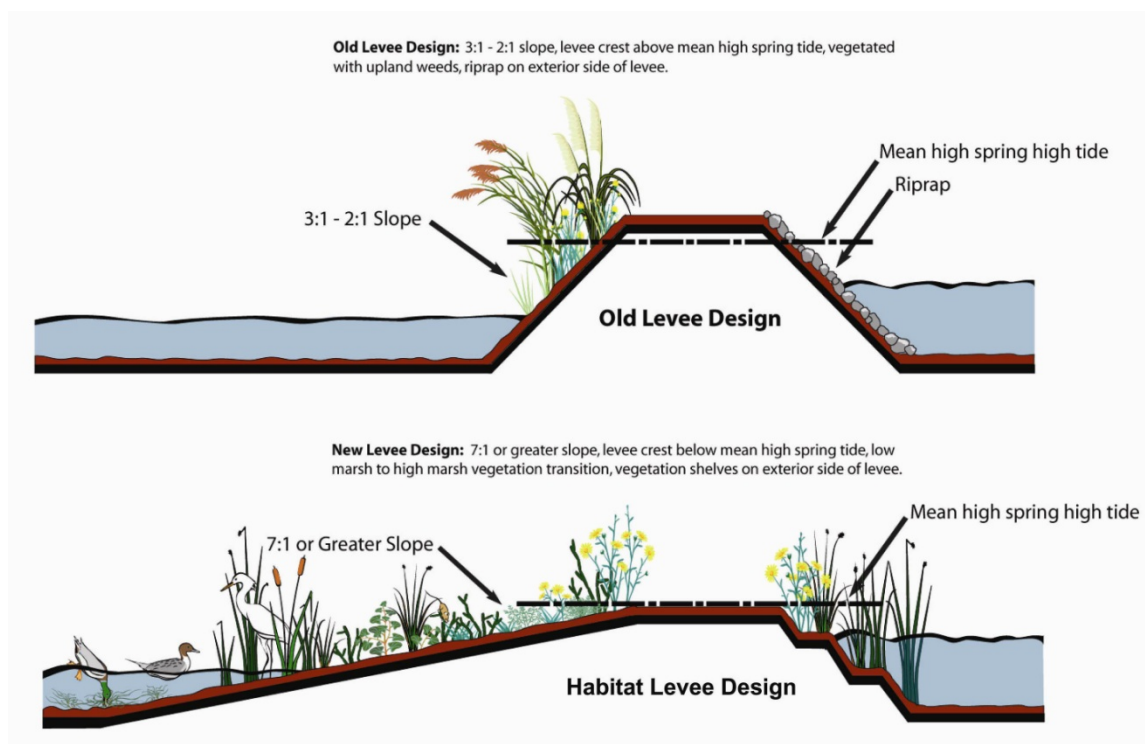


Figure 3-23. Habitat Levee Cross Section

3.6 Assumptions, Uncertainties, and Research Needs

Assumptions

The authors have identified the following assumptions for development of this conceptual model.

1. Structure (form) + process → function
The functions of a tidal marsh are a result of the interactions between the marsh's structure or form and its processes. Changes in the abiotic or biotic structure of the marsh result in a shift in the processes which alter the function of the marsh. For example, a shift in structure such as marsh surface elevation affects processes such as nutrient cycling and plant growth. These changes may result in die out of existing species or colonization by new species, altering the community structure or function.
2. Function supports native species. The general assumption, with some known exceptions, is that natural tidal marsh function supports native species recovery. It is acknowledged, however, that there are some species, such as salt marsh harvest mouse (*Reithrodontomys raviventris*), which may currently have greater recovery in managed marsh areas in Suisun Marsh due to this species' reliance on salt marsh rather than brackish marsh vegetation (which is more characteristic of Suisun) and the need for high tide refugia. This exception derives in part from Suisun Marsh's location at the edge of this species' geographic distribution.

3. Restored tidal marsh systems have a higher probability of self-sustainability than managed systems under changing environmental conditions of sea level rise (SLR) and climate change. The stabilizing morphodynamics feedback of hydroperiod on accretion allows for tidal marshes to maintain a dynamic equilibrium in response to variations in physical conditions such as sea level rise (Friedrichs and Perry 2001). Therefore, as sea levels rise, there is the potential for this feedback mechanism to compensate and maintain equilibrium. In contrast, managed wetlands are dependent on levees and water control structures to control the hydroperiod. Future sea level rise is likely to make these managed areas less sustainable due to the increased cost of levee maintenance and the reduced ability to drain water from the site.
4. The underlying framework for the model is that restored sites will evolve along an 'evolutionary trajectory' resulting in an evolution of topography, hydroperiod, sediment accumulation, plant communities, and aquatic and terrestrial habitats. Various levels of subsidence throughout the Marsh will result in various 'starting points' along this evolutionary trajectory. Time scales of significant geomorphic change are at least decadal.
5. Distributing restoration throughout the Marsh will provide a range of ecological functions that vary seasonally and interannually with varying climatic conditions. This principal is based on the understanding that salinity is a primary driver of ecological function and that Suisun is the location of greatest salinity variation in the Estuary, therefore, locating restoration sites throughout the Marsh will result in salinity variability among the sites with resulting ecological variability.
6. Sites with low-gradient upland edges should be incorporated to allow estuarine marshes to migrate laterally over time to accommodate sea level rise.
7. Sites that are highly subsided will require a longer period of evolution to reach 'dynamic equilibrium', and if they are too low they may never evolve to intertidal marsh. Since subsidence in the Marsh is currently ongoing, it's important to implement restoration activities quickly on sites that are presently close to being 'too low' to restore.
8. Having a suite of restoration sites across the evolutionary gradient that represent different starting points in elevation and provide restoration onto multiple concurrent trajectories leads to the greatest breadth of ecological functions over the longest period of time.
9. Initial stages of restoration at subtidal areas are known to provide ecological functions important to the Estuary even if submerged at all tides. Substantial portions of the Marsh are below MLLW and thus will require longer periods to reach intertidal marsh. These sites may become long-term or permanent subtidal environments where the photic zone reaches the bottom and photosynthetic primary production is high. Connection of these sites to higher-elevation habitats would provide greater ecological function.
10. Well over half of the land area in Suisun Marsh is subsided to intertidal elevations. Another 30% of Suisun Marsh land area is subsided below the tidal frame and is therefore restorable to tidal marsh function only with greater levels of subsidence reversal either through sediment placement and/or biomass production.
11. Levees have considerably reduced habitat connectivity in Suisun Marsh. A basic goal of tidal marsh restoration is to reconnect heterotrophic habitats (sloughs/channels) to autotrophic habitats (tidal shallow water and marsh). Connectivity between the restoration site and the aquatic environments is important to provide the greatest ecological value. Habitats that are connected support more species than disconnected ones (Zedler and Callaway 2001). Shallow water marshes can function as donor habitats by exporting unconsumed phytoplankton biomass to support biological production in deep channel habitats (López et al. 2006; Cloern, 2007). "Habitat connectivity" includes both the physical connection of disparate geomorphic features (like tidal

sloughs and marsh plains) and the exchange and transport of materials from one habitat type to another by tidal action at biologically relevant time scales.

12. Closely related concepts of "residence time," "exposure time," and "flushing time" are key indexes that integrate physical, chemical, and biological processes. They are useful for characterizing rates of habitat connectivity.
13. Pelagic consumers in heterotrophic habitats are routinely food limited because phytoplankton biomass is typically lower than required to sustain maximum rates of growth or reproduction (Mueller-Solger et al. 2002; Sobczak et al. 2002). Therefore, export of production from autotrophic to heterotrophic habitats can be expected to benefit pelagic consumers.
14. Marsh species depend on energy for metabolism, growth, and reproduction. For plants (autotrophs), sunlight supplies the energy that drives photosynthesis and the conversion of carbon dioxide into complex organic molecules. Consumer organisms (heterotrophs) require labile organic matter with high nutritional quality in a form that is consumable.
15. Primary production is highest in shallow water habitats (e.g. Blacklock), inundated floodplains (e.g. Yolo bypass), and tidal sloughs draining mature marsh (Sobczak et al. 2005).
16. Restoration will occur at sites with willing landowners and reliable funding sources, and as a result it will be difficult to predict details of sub-regional implementation.

Several lines of process study must be coordinated and executed in an interdisciplinary fashion.

Coordinated interdisciplinary field studies should include the following components:

- Determine the characteristic population growth rate of producers in donor (tidal restoration) habitats. The critical connectivity rate is defined by the characteristic mean rate of resource exchange.
- The upper limit to system productivity is imposed by factors such as river nutrient inputs and nutrient cycling rates. Measure nutrient cycling in both high and low productivity habitats for evidence of nutrient limitation in productive habitats and possible export of reconstituted nutrients from respiration dominant habitats.
- Investigate mechanical and metabolic constraints on zooplankton growth as a function of food availability. In general, the details of pelagic organic matter transport and secondary production are affected by the region-scale physical constraints on hydrologic connectivity, and micro- scale constraints on individual organism abilities to capture and utilize food. This represents an ecological consequence of physical and biological processes operating over different spatial scales (Thompson et al. 2001; Cloern, 2007).
- In situ toxicants are a fact of life in Suisun Marsh. Employ mesocosms and other techniques to determine the fate and transport of toxic substances including methyl mercury. A significant portion of this effort would be determination of sediment transport characteristics throughout the year.
- Habitat connectivity is important to the ecological productivity of a site. The effects of decreased habitat connectivity in the marsh due to the SMSCG and other water control structures on aquatic species such as delta smelt, longfin smelt, splittail, and resident native species should be evaluated.
- Investigate effects of marsh geomorphology on delta smelt and longfin smelt use of Suisun Marsh.
- Determine the importance of turbidity in comparison to other water quality parameters, to longfin smelt use of Suisun Marsh.

- Evaluate the importance of invertebrate community composition to delta and longfin smelt use of Suisun Marsh.
- Central Valley fall/late-fall, Sacramento River winter-run and Central Valley spring-run Chinook salmon - habitat utilization and residence time in the marsh.
- Central California Coast and Central Valley steelhead - habitat utilization and residence time in the marsh.
- Green sturgeon - habitat utilization, water quality preferences and residence time in the marsh.
- California clapper rail – effects of contaminants, connectivity, salinity, and use of dredge material to accelerate the restoration process.
- Salt marsh harvest mouse – effects of other rodent species, non-native invasive plant species, connectivity, effects of contaminants, and geomorphology.
- Salt marsh common yellowthroat – connectivity, effects of non-native invasive plant species, inundation regime, and brown headed cowbirds.